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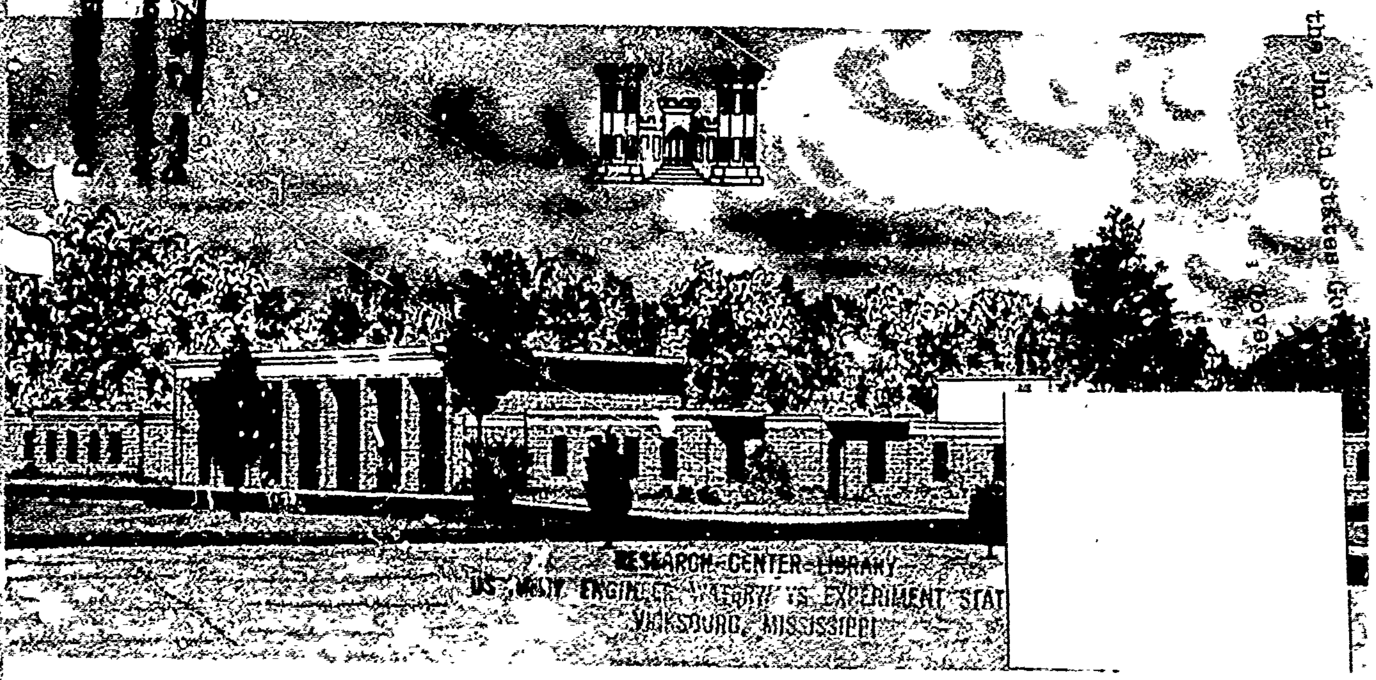
MISCELLANEOUS PAPER C-70-10

TESTS OF ROCK CORES MICHIGAMME STUDY AREA, MICHIGAN

by

R. W. Crisp



June 1970

Sponsored by Space and Missile Systems Organization, Air Force Systems Command

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

ASSOCIATED REPORTS

Report No.	Title	Date
MP C-69-3	Tests of Rock Cores, Warren Area, Wyoming	March 1969
MP C-69-12	Tests of Rock Cores, Mountain Home, Idaho, and Fairchild, Washington, Areas	September 1969
MP C-69-16	Tests of Rock Cores, Castle Study Area, California	October 1969
MP C-70-4	Tests of Rock Cores, Bergstrom Study Area, Texas	February 1970
MP C-70-6	Tests of Rock Cores, Scott Study Area, Missouri	May 1970
MP C-70-7	Tests of Rock Cores, Plattsburgh Study Area, New York	June 1970
MP C-70-9	Tests of Rock Cores, Duluth-Vermillion Study Area, Minnesota	June 1970

TELEPHONE OR VERBAL CONVERSATION RECORD

For use of this form, see AR 340-15; the proponent agency is The Adjutant General's Office.

DATE: 29 February 1972

SUBJECT OF CONVERSATION: Distribution Statement on Reports

INCOMING CALL

PERSON CALLING	ADDRESS	PHONE NUMBER AND EXTENSION

PERSON CALLED	OFFICE	PHONE NUMBER AND EXTENSION

OUTGOING CALL

PERSON CALLING	OFFICE	PHONE NUMBER AND EXTENSION
Mr. James M. Polatty	Concrete Division	

PERSON CALLED	ADDRESS	PHONE NUMBER AND EXTENSION
Captain B. W. Bullard	Space & Missile Systems Organization	

SUMMARY OF CONVERSATION

I called SAMSO and talked to CPT Bullard. CPT Bullard was familiar with the WES reports covering rock tests for SAMSO. I explained the requirements of AR 70-31. He agreed that Statement A should be utilized on all of the SAMSO rock test reports.

James M. Polatty

JAMES M. POLATTY, Chief
Engineering Mechanics Branch
Concrete Division

Copy furnished:
Publications-Distribution

Laura Hanisee said following MP's/covering rock tests for SAMSO were to be changed to Statement A:

C-69-3
C-70-12
C-70-16
[illegible]
[illegible]
C-70-7
C-70-9
C-70-10
C-70-11
C-70-14
C-70-16
C-70-17

DA FORM 751, 1 APR 66 — REPLACES EDITION OF 1 FEB 58 WHICH WILL BE USED.

MISCELLANEOUS PAPER C-70-10

TESTS OF ROCK CORES
MICHIGAMME STUDY AREA, MICHIGAN

by

R. W. Crisp

June 1970

Sponsored by Space and Missile Systems Organization, Air Force Systems Command

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

[redacted]

ABSTRACT

Laboratory tests were conducted on rock core samples received from six core holes in the Michigamme study area of Marquette and Baraga Counties near Sawyer Air Force Base, Michigan. Results were used to determine the quality and uniformity of the rock to depths of 200 feet below ground surface.

The rock core was petrographically identified as predominately tonalite, potash granite, and amphibolite, with relatively minor amounts of biotite schist and pegmatite. Most specimens contained fractures which ranged in orientation from horizontal to vertical. Several specimens contained well-developed systems of fracture.

Evaluation on a hole-to-hole basis indicates the potash granite removed from Hole MG-CR-2A and the gneissic tonalite and amphibolite removed from Holes MG-CR-26 and -28 to be relatively competent to very competent rock. These holes represent materials which should offer good possibilities as competent, hard rock media.

Hole MG-CR-18 yielded specimens of potash granite, tonalite, and amphibolite. This variety of materials exhibited physical characteristics generally representative of marginal to good quality rock, and should offer some possibility as a competent hard rock medium, provided the single zone of incompetent rock is not a disqualifying factor. The tonalites, amphibolites, and potash granites representative

of Holes MG-CR-10 and -54 were generally fractured and exhibited physical characteristics typical of rock of lower quality than that required of competent media.

The above evaluations have been based on somewhat limited data and, therefore, more extensive investigation will be required in order to fully define the individual areas under consideration.

PREFACE

This study was conducted in the Concrete Division of the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the U. S. Air Force Space and Missile Systems Organization (SAMSO) of the Air Force Systems Command. The study was coordinated with CPT Rupert G. Tart, Jr., SAMSO Project Officer, Norton Air Force Base, San Bernardino, California. The work was accomplished during September of 1969 under the general supervision of Mr. Bryant Mather, Chief, Concrete Division, and under the direct supervision of Messrs. J. M. Polatty, Chief, Engineering Mechanics Branch, W. O. Tynes, Chief, Concrete and Rock Properties Section, and K. L. Saucier, Project Officer. Mr. C. R. Hallford was responsible for the petrography work. Mr. R. W. Crisp performed the majority of the program analysis and prepared this report.

Director of the WES during the investigation and the preparation and publication of this report was COL Levi A. Brown, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows.

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
feet per second	0.3048	meters per second
pounds	0.45359237	kilograms
pounds per square inch	0.070307	kilograms (force) per square centimeter
	6.894757	kilonewtons per square meter

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The purpose of this study was to supplement the information being obtained for the area evaluation study by the U. S. Air Force Space and Missile Systems Organization (SAMSO). It was necessary to determine the properties of the specific materials for (1) evaluation of the area as a hard rock medium, and (2) an analysis of the quality and uniformity of the rock. Results of tests on cores from Baraga and Marquette Counties near Sawyer Air Force Base, Michigan, are reported herein.

1.2 OBJECTIVE

The objective of this investigation was to conduct laboratory tests on samples from areas containing hard, near-surface rock to determine the integrity and the mechanical behavior of the materials as completely as possible, analyze the data thus obtained, and report the results to appropriate users.

1.3 SCOPE

Laboratory tests were conducted as indicated in the two paragraphs following on samples received from the field. Table 1.1 gives pertinent information on the various tests.

Tests conducted to determine the general quality and integrity of the rock in the area sampled were: (1) relative hardness (Schmidt number), (2) specific gravity, (3) unconfined compression (conventional and cyclic compression), (4) elastic moduli, and (5) sonic velocity.

Special tests conducted respectively (1) to determine the degree of anisotropy of the sampled rock and (2) to facilitate comparison of direct and indirect tensile strengths were: (1) dynamic elastic properties along three mutually perpendicular axes and (2) tensile strength. A limited petrographic examination was also made.

1.4 SAMPLES

Samples were received from six holes in the Michigamme area. These holes were designated MG-CR-2A, -10, -18, -26, -28, and -54. All samples were NX-size cores (nominal 2-1/8-inch[1] diameter). Test specimens of the required dimensions as presented in Table 1.1 were prepared for the individual tests. Quality and uniformity tests were conducted on selected specimens from all holes. Special tests were conducted on specimens selected from the various core holes to represent differences in rock type, weathering, etc.

[1] A table of factors for converting British units of measurement to metric units is presented on page 8.

1.5 REPORT REQUIREMENTS

The immediate need for the test results required that data reports be compiled and forwarded to the users as work was completed on each hole. The data reports of the individual test results are included herein as Appendixes A through F.

The core descriptions as originally given in the data reports (Appendixes A through F) were frequently taken from the core logs received with the sample shipments. These descriptions have been changed, where necessary, to reflect the results of the petrographic examination and analysis performed at a later date.

TABLE 1.1 SUMMARY OF TESTS

Test	Specimen Size	Test Equipment	Recording Equipment	Measured Properties	Computed Properties
Relative hardness	1 diameter by 2 diameter	Schmidt hammer	--	Relative hardness	--
Specific gravity		Scales	--	Specific gravity	Density
Indirect tension		440,000-pound test machine	--	Tensile strength	--
Direct tension		30,000-pound test machine	--	Tensile strength	--
Unconfined compression		440,000-pound test machine	X-Y recorder	Compressive strength	--
Cyclic compression		440,000-pound test machine	X-Y recorder	Compressive strength	Young's, shear, and bulk moduli and Poisson's ratio
Dynamic elastic moduli		Pulse generator, amplifiers	Oscilloscope	Compressional and shear velocities	Young's, shear, and bulk moduli and Poisson's ratio
Sonic velocity		Pulse generator, amplifiers	Oscilloscope	Compressional and shear velocities	--
Petrographic examination	Variable	Microscopes, X-ray diffraction	--	Appearance, texture, and mineralogy	--
Three-directional dynamic elastic properties	1 diameter by 1 diameter	Pulse generator, amplifiers	Oscilloscope	Compressional and shear velocities	Young's, shear, and bulk moduli and Poisson's ratio

CHAPTER 2

TEST METHODS

2.1 SCHMIDT NUMBER

The Schmidt number is a measure of the relative degree of hardness as determined by the degree of rebound of a small mass propelled against a test surface. The test was conducted as suggested in Reference 1 (a Swiss-made hammer was used); twelve readings per specimen were taken. The average of these readings is the Schmidt number or relative hardness. The hardness is often taken as an approximation of rock quality, and may be correlated with other physical tests such as strength, density, and modulus.

2.2 SPECIFIC GRAVITY

The specific gravity of the "as-received" samples was determined by the loss of weight method conducted according to method CRD-C 107 of Reference 2. A pycnometer is utilized to determine the loss of weight of the sample upon submergence. The specific gravity is equal to the weight in air divided by the loss of weight in water.

2.3 INDIRECT TENSION

Tensile strength was determined by the indirect method, commonly referred to as the tensile splitting or Brazilian method, in which a tensile failure stress is induced in a cylindrical test specimen by a

compressive force applied on two diametrically opposite line elements of the cylindrical surface. The test was conducted according to method CRD-C 77 of Reference 2.

2.4 DIRECT TENSION

For purposes of comparison, specimens were prepared and tested for tensile strength according to the American Society for Testing and Materials (ASTM) proposed "Standard Method of Test for Direct Tensile Strength of Rock Core Specimens." Tensile splitting tests were conducted on specimens cut adjacent to the direct tensile test specimens.

For the direct tension tests, the specimens were right circular cylinders, the sides of which were straight to within 0.01 inch over the full length of the specimen and the ends of which were parallel and not departing from perpendicularity to the axis of the specimen by more than 0.25 degree. Cylindrical metal caps were cemented to the ends of the specimen and provided the means for applying the direct tensile load. The load was applied continuously by a 30,000-pound-capacity universal testing machine and at a constant rate such that failure occurred within 5 to 15 minutes.

2.5 COMPRESSIVE STRENGTH TESTS

The unconfined and cyclic compression test specimens were prepared according to ASTM and Corps of Engineers standard method of test for triaxial strength of undrained rock core specimens, CRD-C 147

(Reference 2). Essentially, the specimens were cut with a diamond blade saw, and the cut surfaces were ground to a tolerance of 0.001 inch across any diameter with a surface grinder prior to testing. Electrical resistance strain gages were utilized for strain measurements, two each in the axial (vertical) and horizontal (diametral) directions. Static Young's, bulk, shear, and constrained moduli were computed from strain measurements and were based on tangent moduli computed at 50 percent of the ultimate strength. Stress was applied with a 440,000-pound-capacity universal testing machine.

2.6 DYNAMIC ELASTIC PROPERTIES

Bulk, shear, and Young's moduli, Poisson's ratio, compressive velocity, and shear velocity were determined on selected rock specimens by use of the proposed ASTM "Standard Method of Test for Laboratory Determination of Ultrasonic Pulse Velocities and Elastic Constants of Rock."

Specimens were prepared by cutting the ends of the NX core with a diamond blade saw, and grinding these surfaces, with a surface grinder, to a tolerance of 0.001 inch across any diameter.

The test method essentially consisted of generating a wave in the specimen with a pulse generator unit and measuring, with an oscilloscope, the time required for the compression and shear waves to travel the specimen, the resulting wave velocity being the distance

traveled divided by the traveltime. These compressive and shear velocities, along with the bulk density of the specimen, were used to compute the elastic properties. In the case of the special tests used to determine the degree of anisotropy of the samples, compression and shear velocities were measured along two mutually perpendicular, diametrical (lateral) axes and along the longitudinal axis. This was facilitated by grinding four 1/2-inch-wide strips down the sides of the cylindrical surface at 90-degree angles and generating the compressive and shear waves perpendicular to these ground surfaces.

2.7 PETROGRAPHIC EXAMINATION

A limited petrographic examination was conducted on samples selected to be representative of the material received from the several holes. The examination was limited to identifying the rock, determining general condition, identifying mineralogical constituents, and noting any unusual characteristics which may have influenced the test results.

CHAPTER 3

QUALITY AND UNIFORMITY TEST RESULTS

3.1 TESTS UTILIZED

Based on experience accumulated through testing and data analysis of core from study areas previously evaluated,[1] the following physical properties were selected for use in evaluating the quality and uniformity of the Michigamme core: Schmidt number, specific gravity, ultimate uniaxial compressive strength, and compressional wave velocity. Dynamic elastic constants were determined for selected representative specimens and results were compared with static elastic constants determined for these same specimens. Static moduli were based on a Poisson's ratio and tangent modulus of elasticity computed at 50 percent of ultimate uniaxial compressive strength.

The core received from the Michigamme study area was, according to bulk composition, comprised of three principal rock types: (1) amphibolites, (2) granites, and (3) tonalites. Insignificant quantities of other rock types (one specimen of rhyolite, four of biotite schist) were also received from the area. Differences in ultimate uniaxial compressive strength appear to have arisen from variation

[1] A list of associated reports is given on the inside front cover of this report.

in rock type coupled with variation in number, nature, and inclination of fractures present in the individual specimens.

To facilitate analysis, data were generally grouped according to rock type, and, where applicable, these general groupings were subdivided according to physical conditions as defined below:

1. Intact rock core, which was macroscopically free of joints, seams, vesicles, and/or fractures.

2. Moderately fractured rock core containing horizontally or vertically oriented fractures.

3. Critically to highly fractured rock core containing well-developed systems of fracture, or critically oriented fractures, i.e., fractures inclined with respect to the horizontal at angles so as to result in the development of shearing stresses of failure magnitude when the specimen is subjected to relatively low axial stress.

4. Rock containing vesicles.

5. Rock containing open fractures.

Detailed physical test results are presented in Appendixes A through F; summaries of the results are tabulated in the various sections of this chapter.

3.2 TONALITE

Portions of the core received from four holes, MG-CR-10, -26, -28, and -54, were petrographically identified as tonalite and

gneissic tonalite. Physical test results both suggested and reflected subdivision of test results into three groups: (1) intact core, (2) moderately fractured core, and (3) critically to highly fractured core.

A detailed tabulation and discussion of test results are given in Appendixes B, D, E, and F. A summary of these results is given below:

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Uniaxial Compressive Strength	Compressional Wave Velocity
				psi	fps
Intact Core:					
MG-CR-26	8	3.09[illegible]	54.2	42,420	22,480
	10	2.779	61.5	38,940	19,345
MG-CR-28	1	2.790	63.8	35,750	18,715
	5	2.705	63.8	29,820	18,985
	22	2.898	56.7	32,730	20,600
Average		2.853	60.0	35,930	20,025
Moderately Fractured Core:					
MG-CR-10	2	2.711	--	26,540	18,925
	4	2.662	59.0	25,820	18,900
	18	2.659	61.8	27,180	19,410
	23	2.677	61.2	29,240	17,350
MG-CR-26	6	3.070	53.[illegible]	27,580	21,635
MG-CR-28	2	2.988	61.8	18,480	20,655
	6	2.[illegible]97	63.2	22,910	19,760
	21	3.037	63.7	26,550	21,950
MG-CR-54	14	2.704	49.7	17,000	19,670
Average		2.812	59.2	24,590	19,805
Critically to Highly Fractured Core:					
MG-CR-10	5	2.659	55.9	7,700	17,160
MG-CR-54	2	2.667	--	16,360[a]	19,420
	6	2.644	--	3,080	19,540
	7	2.653	41.9	16,480[a]	19,410
	8	2.653	--	2,910	19,360
	18	2.658	--	5,940	19,880
	20	[illegible]	--	5,880	19,550
Average		2.65[illegible]	48.8	8,340	19,190

[a] These specimens were obviously weakened to a lesser degree by the well-developed systems of fracture present in most of the core from Hole MG-CR-54, possibly due to a more advanced degree of healing of these fractures.

The intact tonalite from the Michigamme study area appeared to be quite strong, exhibiting an average ultimate uniaxial compressive strength of approximately 36,000 psi. Fracturing of this material, however, resulted in moderate to severe reductions in strength.

That core which contained horizontal or vertical fractures (moderately fractured) was found to exhibit strengths approximately 70 percent as great as those exhibited by the intact tonalite. In spite of this 30 percent reduction in strength, the moderately fractured core was still judged to be relatively competent material.

Generally, the critically to highly fractured tonalite was found to have been severely weakened by the fracturing. This material exhibited an average ultimate uniaxial compressive strength less than 25 percent as great as the average yielded by the intact material, with most strengths falling in the incompetent range of 0 to 8,000 psi. Two of the highly fractured specimens were substantially stronger than the rest, obviously weakened to a lesser degree by the well-developed systems of fracture. These two specimens should by no means be judged as representative of the critically to highly fractured core as the majority of the ultimate strengths fell well below the 8,000-psi mark.

Compressional wave velocities determined for the tonalite reflected, to a much lesser degree, the fracturing present in much of the core. The velocities exhibited by the moderately fractured core

were of only a slightly lower magnitude than those exhibited by the intact material. Critical angle fractures and well-developed systems of fracture had a more pronounced effect on compressional wave velocity, with the group comprised of this type of core exhibiting velocities averaging almost 1,000 fps below the average yielded by the intact tonalite.

As indicated in the tabulation below, elastic constants exhibited

Hole No.	Specimen No.	Specimen Description	Modulus						Poisson's Ratio		Wave Velocity	
			Young's		Bulk		Shear		Static	Dynamic	Compressional	Shear
			Static	Dynamic	Static	Dynamic	Static	Dynamic				
			10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi			fps	fps
NG-CR-2[illegible]	10	Intact	10.8	10.7	7.5	8.5	4.3	4.2	0.26	0.29	19,345	10,540
NG-CR-28	[illegible]	Intact	11.6	10.0	5.0	8.0	4.8	3.9	0.22	0.29	18,715	10,160
	[illegible]	Intact	12.5	11.9	8.5	10.4	5.0	5.6	0.25	0.31	20,600	10,815
NG-CR-54	8	Highly fractured	9.3	9.5	6.2	8.6	3.7	[illegible]	[illegible]	0.32	19,360	10,050
	18	Highly fractured	9.7	9.8	6.5	9.2	3.9	3.7	[illegible]	0.32	19,680	10,160
Average			10.8	[illegible]	6.7	[illegible]	4.3	4.2	[illegible]	0.31	[illegible]	10,340

by the tonalite were rather high, with static elastic Young's moduli generally found to be slightly larger than their corresponding dynamic values. Moduli yielded by the highly fractured core were found to be only slightly lower than those determined for the intact material.

As indicated by the cyclic stress-strain curves reported in Appendixes D, E, and F, the intact tonalite from this area was found to be quite brittle, whereas the highly fractured material was not.

Little hysteresis was exhibited and no appreciable residual strain was detected.

3.3 POTASH GRANITE

Portions of the core received from Holes MG-CR-2A, -10, and -18 were petrographically classified as potash granite. Results of physical tests were grouped according to physical condition of the as-received core. These groupings were: (1) intact rock, (2) moderately fractured rock, (3) rock containing critically oriented fractures, and (4) rock containing open fractures and/or vesicles.

Physical test results are given in detail in Appendixes A, B, and C. A summary of the results is given below:

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Uniaxial Compressive Strength	Compressional Wave Velocity
				psi	fps
Intact Core:					
MG-CR-2A	4	2.629	51.9	40,910	19,190
	7	2.613	53.5	39,090	19,510
	14	2.640	50.9	31,820	18,360
	20	2.628	55.2	34,850	18,965
Average		2.628	52.9	36,670	19,010
Moderately Fractured Core:					
MG-CR-18	1	2.641	52.9	23,120	19,510
	3	2.685	52.0	30,310	19,580
	5	2.681	49.5	18,110	18,880
	8	2.654	51.4	18,210	19,440
	11	2.636	--	23,940	19,460
Average		2.659	51.4	22,740	19,3[illegible]0

(Continued)

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Uniaxial Compressive Strength	Compressional Wave Velocity
				psi	fps
Core Containing Critically Oriented Fractures:					
MG-CR-10	8	2.661	57.1	14,090	19,080
MG-CR-18	4	2.667	37.4	11,090	17,540
	6	2.669	--	14,000	18,460
Average		2.666	47.2	13,060	18,360
Core Containing Open Fractures or Vesicles:					
MG-CR-10	12	2.494	28.3	7,820	18,800
	14	2.499	--	5,200	12,880
MG-CR-18	15	2.662	--	5,240	18,090
Average		2.552	28.3	6,090	16,590

The intact potash granite from the Michigamme study area was very strong, comparable to the intact tonalite previously discussed. As with the tonalite, however, fracturing of the granite generally resulted in moderate to severe reductions in ultimate uniaxial compressive strength.

The moderately fractured granite (containing vertical or horizontal fractures) exhibited an average ultimate strength approximately 60 percent as large as that yielded by the intact granite. There was, however, an appreciable range in strengths observed (18,000 to 30,000 psi). The apparent reduction in strength due to the presence of fractures was quite similar to that observed for the tonalites. As indicated by the range of ultimate strengths yielded

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Elastic constants determined for the intact granite (tabulated below) were relatively high, camparable to values yielded by the intact tonalite. Dynamic constants determined for the vesicular granite (static constants could not be reliably determined) were quite low due to the pronounced decrease in wave velocities caused by the vesicles.

Hole No.	Specimen No.	Modulus						Poisson's Ratio		Wave Velocity	
		Young's		Bulk		Shear		Static	Dynamic	Compres-sional	Shear
		Static	Dynamic	Static	Dynamic	Static	Dynamic				
		10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi			fps	fps
Intact to Moderately Fractured Core:											
MG-CR-2A	14	10.7	10.1	5.9	6.6	4.5	4.1	0.20	0.24	18,360	10,690
MG-CR-18	3	11.3	11.9	6.5	7.4	4.7	4.9	0.21	0.23	19[illegible]	11,600
Average		11.0	11.0	6.2	7.0	4.6	4.5	0.20	0.24	18,[illegible]	11,150
Core Containing Vesicles:											
MG-CR-10	12	--[a]	5.5	--[a]	9.3	--[a]	2.0	--[a]	0.40	18,800	7,635
	14	--[a]	3.8	--[a]	3.7	--[a]	1.4	--[a]	0.33	12,880	6,495
Average			4.6		6.5		1.7		0.36	15,840	7,0[illegible]

[a] Static-elastic constants could not be determined since electrical resistance strain gages could not be applied to the vesicular surfaces of these specimens in a manner so as to obtain reliable results.

Stress-strain curves determined for the intact granite revealed this material to be quite brittle, exhibiting no noticeable plastic deformation prior to catastrophic failure. Upon cycling, these stress-strain curves revealed little hysteresis and no appreciable residual strain.

3.4 AMPHIBOLITE

Portions of the core received from four holes, MG-CR-10, -18,

-26, and -54, were petrographically identified as amphibolite. Physical test results both suggested and reflected subdivision and analysis of the data according to the following: (1) intact rock, (2) moderately fractured rock, and (3) critically to highly fractured rock.

Test results are given in detail in Appendixes B, C, D, and F. A summary of the results is given below:

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Uniaxial Compressive Strength	Compressional Wave Velocity
				psi	fps
Intact Core:					
MG-CR-26	3	2.997	58.8	25,300	21,955
	9	2.840	56.2	29.240	20,415
	21	2.760	61.2	25,900	19,355
Average		2.866	58.7	26,810	20,580
Moderately Fractured Core:					
MG-CR-10	22	3.170	54.5	15,700	21,700
MG-CR-18	12	2.988	45.6	15,850	21,520
	19	2.853	42.6	13,330	20,740
MG-CR-26	16	2.891	5[illegible].1	17,730	20,810
Average		2.975	49.2	15,650	21,210
Critically to Highly Fractured Core:					
MG-CR-10	10	2.706	--	8,210	17,230
	15	2.841	--	12,120	19,395
	16	2.854	46.8	8,000	16,845
	19	2.961	55.3	10,240	22,175
MG-CR-54	1	2.714	37.3	8,790	18,940
	9	2.866	--	4,950	21,620
	11	2.745	--	3,580	20,680
Average		2.812	46.5	7,980	19,560

The amphibolite received from the Michigamme study area appeared to be somewhat weaker in all cases than the tonalites and granites previously discussed.

The intact core exhibited an average ultimate uniaxial compressive strength of 26,810 psi, a value comparable to the average ultimate strengths exhibited by the moderately fractured tonalites and granites.

The moderately fractured amphibolite was somewhat weaker than the intact material, yielding an average ultimate uniaxial compressive strength approximately 60 percent as great as that yielded by the intact amphibolite. This 40 percent reduction in strength compares very well with the 30 to 40 percent reductions apparently caused by moderate fracturing of the tonalites and granites. The moderately fractured amphibolite is still, however, in spite of its somewhat lower strength, relatively competent rock.

The critically to highly fractured amphibolite from the Michigamme study area was found to be substantially weaker than both the intact and moderately fractured amphibolite. This material exhibited an average ultimate uniaxial compressive strength of only 30 percent of that yielded by the intact core, generally falling in the incompetent to marginal range.

Compressional wave velocities determined for the intact and moderately fractured amphibolite were such as to indicate that the

moderate fracturing had little, if any, effect on wave velocity, probably since much of this fracturing was vertically oriented and compressional waves would not necessarily be forced to pass across these fractures. Compressional wave velocities determined for the critically to highly fractured amphibolite were somewhat lower.

As indicated in the following tabulation, elastic constants determined for the amphibolite were slightly scattered. There was detected, however, a definite trend toward higher moduli with higher ultimate compressive strength.

Hole No.	Specimen No.	Modulus						Poisson's Ratio		Wave Velocity	
		Young's		Bulk		Shear		Static	Dynamic	Compressional	Shear
		Static	Dynamic	Static	Dynamic	Static	Dynamic				
		10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi			fps	fps
Intact and Moderately Fractured Core:											
MG-CR-10	22	12.5	12.2	8.7	14.2	5.0	4.5	0.26	0.36	21,770	10,270
MG-CR-18	12	13.4	14.6	7.9	11.0	5.5	5.9	0.22	0.28	21,520	11,870
	19	10.5	13.6	7.0	9.3	4.2	5.4	0.25	0.26	20,740	11,880
MG-CR-26	3	13.8	14.7	9.2	11.8	5.5	5.7	0.25	0.29	21,960	11,880
Average		12.6	13.8	8.2	11.6	5.0	5.4	0.24	0.30	21,500	11,480
Critically to Highly Fractured Core:											
MG-CR-10	15	10.0	9.4	6.9	9.7	4.0	3.5	0.26	0.34	19,400	9,560
	16	7.8	7.7	4.3	7.0	3.2	2.9	0.20	0.32	16,840	8,710
MG-CR-54	1	9.8	8.9	4.7	8.7	4.3	3.4	0.15	0.33	18,940	9,570
Average		9.2	8.7	5.3	8.5	3.8	3.3	0.20	0.33	18,390	9,280

Moduli determined for the intact and moderately fractured core were quite high, with dynamic constants generally found to be slightly higher than the corresponding static values. Moduli determined for the critically to highly fractured amphibolite were somewhat lower,

probably due to the more pronounced effects of fracturing.

Stress-strain curves from which the static constants were determined revealed the amphibolite to be a rather brittle material. With the exception of Specimen 1 from Hole MG-CR-54, the amphibolite cores for which elastic constants were determined exhibited, upon cycling, little hysteresis and no appreciable residual strain. Specimen 1 of Hole MG-CR-54 yielded a stress-strain curve with some initial reverse curvature, probably due to crack closure during the initial stages of loading. The residual strain detected in this specimen was probably due to permanent displacement along the critical angle fractures.

3.5 PEGMATITE

Several specimens received from Holes MG-CR-26 and -28 were petrographically identified as pegmatite. All of these cores were intact, and, as indicated in the summary of physical test results below, exhibited rather uniform physical properties. Detailed test results are given in Appendixes D and E.

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Uniaxial Compressive Strength	Compressional Wave Velocity
				psi	fps
MG-CR-26	4	2.668	65.1	33,180	19,120
	12	2.691	60.2	21,060	19,110
	19	2.673	53.1	31,140	18,020
MG-CR-28	8	2.658	65.2	30,610	19,445
	10	2.677	--	35,000	19,010
	18	2.671	63.8	41,200	19,375
Average		2.673	61.5	30,360	19,010

The pegmatites from the Michigamme study area yielded ultimate uniaxial compressive strengths only slightly lower in magnitude than those exhibited by the intact tonalites and granites from this same area. Compressional wave velocities were very uniform, averaging approximately 19,000 fps.

As indicated in the tables of elastic constants in Appendixes D and E, the moduli determined (two specimens) for the pegmatite cores were moderately high, but again slightly lower than those determined for the intact tonalites and granites. This material is quite brittle, and as indicated by cyclic compression stress-strain curves, exhibits no appreciable hysteresis or residual strain.

3.6 BIOTITE SCHIST

Also received from the Michigamme study area were four specimens of biotite schist. A summary of test results for the four schist specimens is given below. Detailed results are given in Appendix A.

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Uniaxial Compressive Strength	Compressional Wave Velocity
				psi	fps
MG-CR-2A	1	2.788	--	18,030	19,480
	8	2.953	50.0	20,450	21,740
	9	2.719	--	20,150	18,560
	18	2.964	49.5	26,060	21,720
Average		2.856	49.8	21,170	20,380

The biotite gneiss specimens received from this area exhibited rather uniform physical test results; the average ultimate uniaxial compressive strength was found to be approximately 21,000 psi.

Elastic constants were determined for Specimen 18, and, as indicated in Appendix A, were found to be very high; the static Young's modulus was found to be 14.8×10^6 psi. Stress-strain curves plotted during the cyclic compression test revealed the biotite schist to be quite brittle. Upon cycling, no hysteresis or residual strain was detected.

CHAPTER 4

SPECIAL TESTS

4.1 ANISOTROPY TESTS

Eight rock specimens from the Michigamme area were selected and prepared for determination of compressional and shear velocities according to the ASTM proposed "Standard Method of Test for Laboratory Determination of Ultrasonic Pulse Velocities and Elastic Constants of Rock." The NX-diameter specimens were cut to lengths of 2 inches and ground on the ends to a tolerance of 0.001 inch. Four 1/2-inch-wide strips were also ground down the sides of the cylindrical surface at 90-degree angles. The velocities, densities, and dimensions were measured as specified in the proposed test method.

Results of velocity determinations are given in Table 4.1. Compressional and shear wave velocities exhibited by the specimens tested herein were moderate in magnitude, with those yielded by the tonalites generally being slightly higher than those exhibited by the granites.

Deviations from the average compressional wave velocity were, in most cases, rather low--not exceeding 3 percent. Two specimens, however, exhibited deviations from the average of 5 percent or greater; both were horizontally banded gneissic tonalites. In each case, the large deviation was due to relatively low velocities

exhibited in the axial direction perpendicular to the banding.

A compilation of the elastic properties computed from the compressive and shear velocities and the specific gravity is given in Table 4.2. However, discretion must be used in utilizing the moduli results as experimental errors are introduced when the differences in velocities are significant. The proposed ASTM test method states that the equations for computation of elastic moduli should not be used if "any of the three compressional wave velocities varies by more than 2 percent from their average value. The error in E and G due to both anisotropy and experimental error then does not exceed 6 percent." Naturally, the effect of the error is compounded by greater differences in the three-directional velocity measurements.

The 2 percent allowable deviation proposed by ASTM appears to be unrealistic since laboratory-determined values of compressional and shear wave velocities are reproducible within a deviation from the average of only 2 to 3 percent. Thus, it would appear that the point of division between isotropy and anisotropy would more realistically be in the range of 5 to 8 percent deviation from the average. It should be kept in mind, however, that this greater deviation would also allow a larger error in the computed values of E and G .

4.2 COMPARATIVE TENSILE TESTS

Eight NX-diameter rock specimens were selected in an attempt to

represent the variation of rock type present in the core received from the drill holes in the Michigamme area. Tonalite and granite specimens were present in sufficient quantity and length to permit testing several of each type. Amphibolite specimens available, however, were too short to allow comparative tensile tests on specimens of this rock type.

The specimens were prepared and tested for tensile strength according to the ASTM proposed "Standard Method of Test for Direct Tensile Strength of Rock Core Specimens." For comparative purposes, tensile splitting tests were conducted on specimens cut adjacent to the direct tensile test specimens. The test results are given in Table 4.3.

Two specimens failed through the epoxy bonding agent on the initial direct tension test attempts. These specimens were then turned on a lathe, gradually reducing specimen diameter from 2 inches at either end to 1.5 inches along a 1-inch-long central section (dogbone). This section was sufficiently reduced to result in tensile failure at loads low enough to be held by the epoxy adhesive.

Direct tensile strengths were rather high and, except for the highly fractured specimen of gneissic tonalite, ran above 900 psi. The severely fractured gneissic tonalite exhibited a direct tensile strength of 580 psi and an indirect strength of 1,360 psi. The direct tensile strength should better reflect the true tensile strength

of the rock, since a specimen subjected to direct tension is more prone to failure at the point of minimum strength, i.e., along fractures, etc.

Indirect tensile strengths, with two exceptions, ran somewhat higher than the corresponding direct tensile strengths, probably due to the more restricted location of the failure surface in the indirect test. Therefore, there is less probability of failure occurring at a point of minimum strength.

4.3 PETROGRAPHIC EXAMINATION

4.3.1 Samples. Six boxes of NX core from holes in Baraga and Marquette Counties, Michigan, were received for testing in August 1969. Each box contained about 15 feet of core which represented several depths to 200 feet.

The cores were inspected to select representative pieces from all significant rock types for petrographic examination. The cores are described below:

1. Hole MG-CR-2A. The core was a mixture of pink and black, medium-grained granite and a black fine-grained biotite schist identified in the field log as amphibolite. Only Specimens 6 and 13 and parts of Specimens 1 and 9 were biotite schist. All the sections were intact.

2. Hole MG-CR-10. Several rock types including granite,

tonalite, and amphibolite were present. All the specimens inspected contained fractures, except Specimens 3, 12, 13, 20, and 21 which were intact.

Specimens 1 through 6, 18, and 23 were red and brown, coarse-grained tonalites. Most of the sections had bright red patches of hematitic stain and contained many sealed fractures. Specimens 1 through 6 appeared slightly weathered.

Specimens 7, 8, 9, and 11 through 14 ranged from red, fine-grained rhyolitic rocks to red, medium-grained granitic rocks. Specimen 7 contained the contact between a red, fine-grained rhyolite and a gray and green gneissic rock. Specimens 8, 9, and 11 through 14 were bright red, medium-grained rocks. All but Specimens 12 and 13 had been severely fractured. Many of the fractures had been sealed with quartz or calcite.

Specimens 10, 15, 16, 17, and 19 through 22 were dark green, fine- to medium-grained metamorphic rocks identified as amphibolites. Specimens 19 and 20 were schistose and the remaining specimens were gneissic. Specimens 21 and 22 appeared to contain more quartz than the other specimens.

3. Hole MG-CR-18. The core was blackish-red, fine- to medium-grained granite; black, fine-grained amphibolite; and red and black, medium- to coarse-grained tonalite. Most of the specimens contained fractures or joints but none of the sections appeared weathered.

Specimens 1, 3 through 6, 8 through 11, and 15 were dark red, medium- to fine-grained granite. Specimens 4, 6, and 15 had fractures at the critical angle. Specimen 4 also contained a large schistose inclusion.

Specimens 12 and 19 were black, fine-grained amphibolites and contained several high-angle fractures.

Specimens 2, 7, 13, 14, 16, 17, and 18 were black and red, medium- to coarse-grained, irregularly banded tonalite. These specimens contained broad irregular bands of biotite and chlorite, and many sealed fractures.

4. Hole MG-CR-26. The core was black amphibolite and black and white, medium-grained gneissic tonalite. Specimens 3, 5, 7, 9, 13 through 17, 20, 21, and 23 were amphibolite. Specimens 6, 8, and 10 were a fine-grained, gray-green tonalite that may have been an inclusion in the amphibolite. Specimens 1, 2, 4, 11, 12, 18, 19, 22, and 24 were gneissic tonalite, not as dark as the previously mentioned sections of amphibolite, and did not contain any visible fractures.

Specimens 4, 12, 17, and 19 contained contacts with pink and white pegmatites. Specimens 5, 16, and 23 contained tightly closed fractures. None of the sections appeared weathered.

5. Hole MG-CR-28. The core was black and white, fine- to medium-grained gneissic tonalite. Only Specimens 2, 3, 6, 15, 18, and 21 contained fractures. All of Specimens 17 and 18 and parts of

Specimens 3, 8, 10, and 11 were pegmatites.

6. Hole MG-CR-54. The core was severely fractured gneissic tonalite and dark green, medium-grained amphibolite. Specimens 1, 9, and 11 were severely fractured amphibolite and the remainder of the core was highly fractured gneissic tonalite. The major set of fractures ranged from 45 degrees to nearly vertical. There was marked reduction in grain size along the shear fractures.

The specimens selected for petrographic examination were:

Hole No.	Concrete Division Serial No.	Specimen No.	Approximate Depth	Rock Description
			feet	
MG-CR-2A	SAMSO-9, DC-5	9	96	Gray and black, coarse-grained tonalite with a high-angle biotite schist band 1 inch thick.
		20	195	Pink and black, medium-grained granite.
MG-CR-10	SAMSO-9, DC-1	6	74	Brown and red, coarse-grained gneissic tonalite.
MG-CR-10	SAMSO-9, DC-1	7	83	Contact between green and white, coarse-grained gneiss and red, fine-grained rhyolite.
MG-CR-10	SAMSO-9, DC-1	13	130	Red, highly fractured granite.

(Continued)

Hole No.	Concrete Division Serial No.	Specimen No.	Approximate Depth	Rock Description
			feet	
MG-CR-10 (Continued)	SAMSO-9, DC-1	17	156	Contact between dark, medium-grained, gneissic amphibolite and dark, medium-grained amphibolite.
		19	176	Green, medium-grained amphibolite.
		21	186	Dark, medium-grained amphibolite.
MG-CR-18	SAMSO-9, DC-6	9	113	Blackish-red, fine-grained granite.
		12	130	Black, fine-grained amphibolite.
		16	171	Red and black, medium- to coarse-grained tonalitic rock similar to MG-CR-1[illegible], Specimen 9, but this specimen contained a pegmatitic band.
		17	181	Red and black, medium- to coarse-grained tonalitic rock with disrupted pegmatite bands.
MG-CR-26	SAMSO-9, DC-2	2	17	Black and white, medium-grained gneissic tonalite.

(Continued)

Hole No.	Concrete Division Serial No.	Specimen No.	Approximate Depth	Rock Description
			feet	
MG-CR-26 (Continued)	SAMSO-9, DC-2	7	57	Black, medium-grained amphibolite with a high-angle 1/2-inch quartz band.
		10	88	Gray-green, fine-grained tonalite.
		17	146	Contact between pink and white pegmatite and black and white amphibolite similar to contact in Specimen 2 of this hole.
MG-CR-28	SAMSO-9, DC-3	3	28	Black and white, coarse-grained tonalite partially altered pink; large disrupted quartz pods.
MG-CR-28	SAMSO-9, DC-3	13	114	Black and white, coarse-grained tonalite with a low-angle 2-inch fine-grained tonalite band similar to the tonalite of MG-CR-26, Specimen 2.
MG-CR-54	SAMSO-9, DC-4	16	157	Pink and black, medium-grained gneissic tonalite with numerous sealed fractures.

4.3.2 Test Procedure. Each core specimen was sawed axially. One sawed surface of each specimen was polished and photographed.

Composite samples were obtained from the whole length or from selected portions from the remaining half of each piece. The composite samples were ground to pass a No. 325 sieve (44 μm). X-ray diffraction (XRD) patterns were made of each sample as a tightly packed powder. All XRD patterns were made using an XRD-5 diffractometer with nickel-filtered copper radiation. The samples X-rayed are listed below:

Hole No.	Specimen No.	Description of X-Ray Sample
MG-CR-2A	9	a. Coarse-grained gneiss. b. Dark band cutting the gneiss.
	20	Entire length of core.
MG-CR-10	6	Entire length of core.
	7	a. Green and white gneiss. b. Red, fine-grained rock. c. Light green inclusion in the red rock.
	13	Entire length of core.
	17	a. Foliated half of core. b. Nonfoliated half of core.
	19	Entire length of core.
	21	Entire length of core.
MG-CR-18	9	Entire length of core.
	12	Entire length of core.
	16	Entire length of core.
	17	Entire length of core.

(Continued)

Hole No.	Specimen No.	Description of X-ray Sample
MG-CR-26	2	a. Salt and pepper portion of core. b. Solid black portion of core.
	7	a. Black half of core. b. Black and white half of core.
	10	Entire length of core.
MG-CR-28	3	a. Black and white half of core. b. Pink, altered half of core.
	13	a. Coarse-grained gneiss. b. Fine-grained gneissic band.
MG-CR-54	16	Entire length of core.

Small portions of the powdered samples were tested with dilute hydrochloric acid and with a magnet to determine whether carbonate minerals or magnetite were present.

The polished surface of each section was examined with a stereomicroscope. Thin sections were prepared from each section of core and examined with a polarizing microscope. A point-count modal analysis was made on each thin section in which 500 points were counted.

4.3.3 Results. The cores examined from the Michigamme area can be divided into three principal groups, according to bulk composition: (1) tonalites, (2) granites, and (3) amphibolites (Reference 3). Several specimens from the area (rhyolite, pegmatite, and

biotite schist) did not follow the overall grouping. The rhyolite is discussed with the granites and the biotite schist is discussed with the tonalites. The pegmatites were not examined. All of the cores were taken from the Precambrian rocks north and south of the Marquette Iron District (Reference 4). Cores MG-CR-10 and -2A were taken from the highly deformed igneous and metamorphic rocks of the Southern Complex near Republic, Michigan (References 4 and 5). The Republic area represents a center of intense metamorphism, characterized by sillimanite and staurolite gneiss and schists (Reference 6). Away from this center, the effects of the metamorphism diminish with increasing distance. In this area, intense deformation, represented by shearing, is found in rocks of low metamorphic rank while rocks of higher metamorphic rank are less deformed. The metamorphic zones do not correlate directly with changes in structure and fabric of the rocks produced by deformation (Reference 6).

The remaining cores were taken from the igneous and metamorphic rocks north of the Marquette Iron District, where effects of metamorphism were less than in the Republic area, but where there had been considerable faulting. The rocks in this northern area were predominantly tonalites with minor amounts of granites and amphibolites. The rocks from the Republic area showed the greatest range in rock type, with granite more abundant than tonalites or amphibolites. The modal composition of each rock type is shown in Tables 4.4, 4.5, and

4.6 and the bulk composition by XRD in Tables 4.7, 4.8, and 4.9. The rocks in the cores are discussed below:

1. Tonalites. Cores MG-CR-28 and -54 and parts of Cores MG-CR-2A, -10, -18, and -26 were tonalites which ranged from fine- to coarse-grained and from severely sheared to intact. All of the rocks had been metamorphosed and several had been severely sheared. The metamorphism and shearing often obscured the original character of the rocks. Most of the sections appear to have been igneous tonalites before metamorphism or shearing. The tonalites in Cores MG-CR-2A and -10 were the most metamorphosed and the other cores were more highly sheared.

Section 9 of Core MG-CR-2A differed from most of the rock in Core MG-CR-2A. It was a small volume of biotite schist and tonalite (Figure 4.1). The remainder of the core was granite with minor amounts of biotite schist. The tonalite was black and white, coarse-grained, and may have been an inclusion. The section had been recrystallized which obscured the contacts of the tonalite and the schist.

Section 6 of Core MG-CR-10 was typical of the tonalites in this core from south of the Marquette Iron District. It was red and brown, coarse-grained tonalite that was partially iron stained (Figure 4.1). The section was fractured and sheared and then was strongly metamorphosed, sealing the fractures and in part

recrystallizing the rock. Plagioclase grains were partially stained with hematite and severely altered to sericite; some were granulated. Some of the quartz grains were recrystallized composites of unstrained grains, but many showed considerable strain. Biotite was almost completely altered to chlorite and magnetite.

Section 16 of Core MG-CR-18 was a red and black, medium- to coarse-grained soda tonalite. The section contained two large fractures and several microfractures (Figure 4.2). This section contained more microcline than the other tonalites from this core, which may have been due to partial assimilation by the granitic rocks that were found in the upper part of the core. The minerals in this section had been sheared and altered, except the microcline which was very fresh and apparently had not been affected by the shearing.

Section 17 of Core MG-CR-18 was similar to Section 16 of this core except that this section contained less microcline and more chlorite. This section had apparently been folded, as it was vaguely banded and the bands were disrupted (Figure 4.2). There were several high-angle fractures and many microfractures in the section.

Section 2 of Core MG-CR-26 was black and white, medium-grained gneissic tonalite with a small amount of amphibolite at one end of the section (Figure 4.3). The gneissic structure and the presence of secondary epidote and chlorite indicate that the section had been metamorphosed. The section also had been sheared, as several

microfractures were present. Quartz was broken and strained; plagioclase grains had granulated borders; and biotite flakes were bent and broken. The plagioclase, with anorthite content of 55 percent, apparently was affected by the metamorphism as secondary epidote surrounded by albite rims was present as clots along borders of the grains. This gneiss was often cut by pegmatites, as in Section 17 of Core MG-CR-26 (Figure 4.3).

Section 10 of Core MG-CR-26 had a composition similar to Section 2 of MG-CR-26, but was darker, fine-grained, and more severely altered (Figure 4.4). The section had a cataclastic texture and contained several fractures. Epidote and chlorite were the most common metamorphic products. Plagioclase was almost entirely altered to sericite, which prevented determination of the anorthite content. Quartz had been broken and strained and biotite flakes were bent, broken, and partially altered to chlorite.

Section 3 of Core MG-CR-28 contained a disrupted contact between an altered gneissic tonalite and a pegmatite (Figure 4.5). The tonalite was medium-grained and had been severely sheared and altered. Most of the grains were bent or broken and microfractures were common. Plagioclase was almost entirely altered to sericite. Epidote, chlorite, and sphene appear as secondary minerals at the expense of plagioclase and biotite. Calcite was introduced after shearing along fractured planes.

The pegmatite had been severely faulted and folded. There was very little alteration detected and, as in the tonalite, the most dominant feature of the pegmatite was the severe shearing.

Section 13 of Core MG-CR-28 was a black and white, medium-grained biotite, hornblende, gneissic tonalite, with a 2-inch-thick band of gray fine-grained tonalite gneiss (Figure 4.5). Half of the section (13a) had a low-angle foliation that paralleled the contact with, and the foliation of, the fine-grained band. The remaining half (13b) of the medium-grained tonalite had a poorly developed vertical foliation. The low-angle foliation in the fine-grained band and the lower half of the medium-grained tonalite appeared to be the result of shearing rather than primary flow. Along this contact between the poorly foliated upper tonalite and the fine-grained band, there had been grain reduction, apparently due to differential movement after cooling.

The fine-grained band (MG-CR-28-13b) does not represent a ground up portion of the medium-grained tonalite because there was no trace of hornblende in the fine-grained band while it is abundant in the coarser grained portion. This band may have been a dike or an inclusion that was subsequently sheared.

In the section, plagioclase was altered to sericite and to epidote along shears. Quartz was strained and broken, and biotite and hornblende were partially altered to chlorite.

Section 16 of Core MG-CR-54 was a severely fractured, pink and black, medium-grained gneissic tonalite (Figure 4.4). The section was sheared, with severe grain-size reduction along fracture planes. There had been complete alteration of biotite to chlorite, but only minor alteration of plagioclase to sericite. This section shows the greatest effect of shearing of any of the rocks from the Michigamme area. Plagioclase grains were bent and broken; quartz grains were strained and broken; and the numerous fractures destroyed any trace of the original texture.

2. Granites. Parts of Cores MG-CR-2A, -10, and -18 were granites which ranged from fine to coarse grained and were potash granites (except for MG-CR-10, Section 7, which was a rhyolite) according to the Shand classification (Reference 3). The granites were most abundant in Cores MG-CR-2A and -18 and were a minor occurrence in MG-CR-10.

Section 20 of Core MG-CR-2A was a pink and black, medium-grained potash granite. The section was intact and contained a poorly developed high-angle foliation (Figure 4.6). Plagioclase was slightly altered to sericite and biotite was partially altered to chlorite. Quartz grains were not broken or strained. Plagioclase, with an anorthite content of 28 percent (oligoclase), and microcline grains exhibited excellent crystal shape and very few inclusions.

Section 7 of Core MG-CR-10 was not a granite, but had a bulk

composition that caused it to be placed into the granite group as it was a red, fine-grained rhyolite (Figure 4.7). This section appeared to be a dike rock as indicated by its small volume, chilled contacts, inclusions of wall rocks, and fine-grained texture. The rhyolite intruded and included a chlorite-quartz schist (Figure 4.7). The section contained several finely vesicular areas that may have been devitrified.

Section 13 of Core MG-CR-10 was red, severely sheared, medium- to fine-grained potash granite (Figure 4.7). The shear fractures were sealed quartz, calcite, or hematite. Several vugs were present in the calcite. This section was the most severely sheared section in Core MG-CR-10. The section contained a well-developed cataclastic texture dominated by the numerous shear fractures cutting the section. All of the primary minerals--quartz, microcline, and plagioclase--were strained, bent, and broken. Plagioclase, with an anorthite content near 20 percent (oligoclase), was severely altered to sericite and stained with hematite. Microcline was the least altered mineral with minor amounts of breakage and iron stain.

Section 9 of Core MG-CR-18 was typical of the granites in Core MG-CR-18 (Figure 4.6). The section was blackish-red, fine-grained potash granite that had been severely altered and sheared. Plagioclase grains were broken and altered to sericite, and sphene had been altered to clay. Quartz grains were strained and broken. This

section contained less quartz and more accessory minerals than the granites from cores drilled south of the Marquette Iron District.

3. Amphibolites. Parts of Cores MG-CR-10, -18, and -26 represented the least abundant group of rocks, fine- to coarse-grained amphibolites that ranged from intact to severely sheared.

Section 17 of Core MG-CR-10 contained an amphibolite schist and an amphibolite gneiss. The rocks had similar compositions but varied considerably in texture and grain size (Figure 4.8). Both rocks were cut by parallel low-angle fractures that were slightly offset at the contact.

Green hornblende and plagioclase were the major constituents of both of the rocks. In the gneiss, the plagioclase had been completely altered to sericite and the hornblende had undergone partial solution and recrystallization. In the schist, the minerals had been severely crushed and altered.

The similar mineral composition of the two rocks and the sheared texture of the schist suggest that the schist was the sheared equivalent of the gneiss.

Section 19 of Core MG-CR-10 was green and brown, fine-grained amphibolite schist with a well-developed planar structure (Figure 4.8). The hornblende occurred as needle-like laths that were frequently altered to chlorite. Biotite was also severely altered to

chlorite. There were many microfractures which suggested that the rock was severely sheared.

Section 21 of Core MG-CR-10 was a dark green, medium-grained amphibolite gneiss that was inconspicuously banded and highly fractured (Figure 4.9). The hornblende was very fresh and was only partially crushed along fractures. This section contained more quartz than the typical amphibolites from this core, but was the least altered of all the amphibolites. Pyrite was common along fractures.

Section 12 of Core MG-CR-18 was highly fractured and severely altered, black, fine-grained amphibolite (Figure 4.10). Secondary chlorite was common throughout the section. Plagioclase was almost entirely altered to sericite and hornblende was recrystallized as chlorite. Most of the effects of the shearing had been masked by the alteration and recrystallization.

Section 7 of Core MG-CR-26 was a black and white, medium-grained amphibolite gneiss cut by a high-angle quartz-plagioclase pegmatite (Figure 4.9). The section consisted primarily of blue-green hornblende and plagioclase, with an anorthite content of 42 percent (andesine). Most of the hornblende grains were broken or crushed. Plagioclase was generally fresh except along crushed grain boundaries where it was highly altered to sericite.

4.3.4 Summary. Petrographic examination of 19 sections of core from six holes in Marquette District of northern Michigan indicated

that there were three major rock types represented: tonalites, granites, and amphibolites; the tonalites were the most abundant. Differences in compressive strength and elastic properties within each rock type appear to have arisen from the number and inclination of fractures and whether or not the fractures were open or sealed. Weathering and metamorphic recrystallization appear to have had little effect on the strength of the rocks within each group. The mineral compositions are summarized in Tables 4.4 through 4.9 and the sections examined are illustrated in Figures 4.1 through 4.10.

TABLE 4.1 VELOCITY DETERMINATIONS

	Velocity[a] Compressional	Velocity[a] Shear
	fps	fps
Hole MG-CR-2A, Specimen 5:		
Granite	18,690	9,350
Depth: 62 feet	18,810	9,290
Specific gravity: 2.616	17,990	9,050
Compressional deviation:[b] 2.8 pct		
Average	18,500	9,230
Hole MG-CR-2A, Specimen 13:		
Granite	16,560	6,910
Depth: 135 feet	16,040	8,190
Specific gravity: 2.644	16,850	8,750
Compressional deviation: 2.7 pct		
Average	16,480	7,950
Hole MG-CR-18, Specimen 2:		
Tonalite	19,030	9,570
Depth: 37 feet	19,770	9,650
Specific gravity: 2.676	19,640	9,760
Compressional deviation: 2.3 pct		
Average	19,480	9,660
Hole MG-CR-18, Specimen 18:		
Tonalite	19,430	9,550
Depth: 193 feet	19,220	9,550
Specific gravity: 2.831	19,650	9,530
Compressional deviation: 1.1 pct		
Average	19,430	9,540
Hole MG-CR-26, Specimen 22:		
Gneissic tonalite	17,840	9,590
Depth: 186 feet	18,550	9,440
Specific gravity: 2.668	18,380	9,640
Compressional deviation: 2.3 pct		
Average	18,260	9,560
Hole MG-CR-28, Specimen 15:		
Banded gneissic tonalite	18,850	9,430
Depth: 134 feet	21,700	9,790
Specific gravity: 2.769	21,640	9,880
Compressional deviation: 9.1 pct		
Average	20,730	9,700
Hole MG-CR-28, Specimen 19:		
Slightly banded gneissic tonalite	17,940	9,060
Depth: 174 feet	19,240	9,390
Specific gravity: 2.675	19,470	9,330
Compressional deviation: 5.0 pct		
Average	18,880	9,260
Hole MG-CR-54, Specimen 17:		
Gneissic tonalite	19,890	9,890
Depth: 167 feet	19,480	9,620
Specific gravity: 2.627	19,450	9,720
Compressional deviation: 1.4 pct		
Average	19,610	9,740

[a] First velocity listed is in axial (longitudinal) direction; other two are on mutually perpendicular, diametral (lateral) axes.

[b] Maximum percent deviation from the average of the compressional wave velocity.

TABLE 4.2 DYNAMIC ELASTIC PROPERTIES

Hole No.	Specimen No.	Moduli Young's	Moduli Shear	Moduli Bulk	Poisson's Ratio	Hole No.	Specimen No.	Moduli Young's	Moduli Shear	Moduli Bulk	Poisson's Ratio
		10^6 psi	10^6 psi	10^6 psi				10^6 psi	10^6 psi	10^6 psi	
MG-CR-2A	5	8.2	3.1	8.2	0.33	MG-CR-26	22	8.6	3.3	7.0	0.30
		8.2	3.0	8.4	0.34			8.5	3.2	8.1	0.33
		7.7	2.9	7.6	0.33			8.8	3.4	7.8	0.31
	Average	8.0	3.0	8.1	0.33		Average	8.6	3.3	7.6	0.31
MG-CR-2A	13	4.7	1.7	7.5	0.39	MG-CR-28	15	8.8	3.3	8.8	0.33
		6.3	2.4	6.0	0.32			9.8	3.6	12.8	0.37
		7.2	2.7	6.5	0.32			10.0	3.6	12.6	0.37
	Average	6.1	2.3	6.7	0.34		Average	9.5	3.5	11.4	0.36
MG-CR-18	2	8.8	3.3	8.6	0.33	MG-CR-28	19	7.9	3.0	7.6	0.33
		9.0	3.4	9.6	0.34			8.6	3.2	9.1	0.34
		9.2	3.4	9.3	0.34			8.5	3.1	9.5	0.35
	Average	9.0	3.4	9.2	0.34		Average	8.3	3.1	8.7	0.34
MG-CR-18	18	9.3	3.5	9.8	0.34	MG-CR-54	17	9.2	3.5	9.4	0.34
		9.3	3.5	9.4	0.34			8.8	3.3	9.1	0.34
		9.3	3.5	10.1	0.35			8.9	3.4	8.9	0.33
	Average	9.3	3.5	9.8	0.34		Average	9.0	3.4	9.2	0.34

TABLE 4.3 TENSILE STRENGTH DETERMINATIONS

Hole No.	Speci- men No.	Depth	Tensile Strength			Core Description
			Splitting	Direct	Direct/ Splitting Strength	
		feet	psi	psi	pct	
MG-CR-2A	5	62	1,240	1,740[a]	140	Granite, pink and black
MG-CR-2A	13	135	1,210	900	74	Granite, pink and black
MG-CR-18	[illegible]	37	2,450	1,150	47	Tonalite, black and red
MG-CR-18	18	193	1,790	1,440[a]	80	Tonalite, black and red
MG-CR-26	22	186	1,780	1,870	105	Gneissic tonalite, black and white
MG-CR-28	15	134	1,520	1,310	86	Gneissic tonalite, black and white
MG-CR-28	19	174	1,500	1,040	69	Gneissic tonalite, black and white
MG-CR-54	17	167	1,360	580	43	Gneissic tonalite, severely fractured

[a] On initial test attempt, specimens failed at the epoxy bond. Cross-sectional area of center portion of specimens was then reduced (dogbone) in order to achieve rock failure under the obtainable adhesive strengths.

TABLE 4.4 MODAL COMPOSITION OF TONALITES

Based on 500 counts per thin section.

Constituent	MG-CR-2A	MG-CR-10	MG-CR-18		MG-CR-26		MG-CR-28				MG-CR-54
	Section 9a	Section 6	Section 16	Section 17	Section 2a	Section 10	Section 3a	Section 3b	Section 13a	Section 13b	Section 16
Quartz	32	37	28	31	33	20	17	28	25	28	31
Plagioclase	54	54	40	46	47	49	54	39	40	57	60
Microcline	--	Trace	23	10	1	Trace	--	--	--	--	--
Biotite	10	Trace	Trace	--	15	17	12	26	16	12	--
Chlorite	4	8	4	8	1	2	3	2	2	--	7
Hornblende	--	--	--	--	Trace	--	--	--	13	--	--
Epidote	Trace	--	--	--	2	9	7	Trace	2	1	--
Magnetite	--	--	1	2	Trace	Trace	Trace	Trace	1	1	--
Pyrite	--	Trace	--	--	Trace	--	--	Trace	--	--	Trace
Hematite	Trace	Trace	--	--	Trace	--	--	--	--	--	--
Sphene	--	--	--	--	Trace	2	Trace	Trace	Trace	Trace	--
Zircon	Trace	--	Trace	--	Trace	Trace	Trace	Trace	Trace	Trace	--
Apatite	Trace	--	Trace	Trace	--	--	Trace	Trace	Trace	Trace	--
Calcite	--	--	3	3	Trace	Trace	3	4	Trace	Trace	2
Clay	--	Trace	--	--	Trace	--	Trace	--	--	--	--

TABLE 4.5 MODAL COMPOSITIONS OF GRANITES AND RHYOLITE

Based on 500 point counts per thin section.

Constituent	Granites			Rhyolite
	MG-CR-2A Section 20	MG-CR-10 Section 13	MG-CR-18 Section 9	MG-CR-10 Section 7
Quartz	36	30	21	30
Microcline	27	28	32	20
Plagioclase	25	35	31	--
Biotite	--	6	2	--
Chlorite	1	Trace	6	20
Magnetite	--	--	1	Trace
Hematite	10	--	--	30
Epidote	--	--	2	--
Sphene	--	--	2	--
Zircon	--	--	Trace	--
Apatite	--	--	1	--
Calcite	1	Trace	1	Trace

TABLE 4.6 MODAL COMPOSITION OF AMPHIBOLITES

Based on 500 point counts per thin section.

Constituent	MG-CR-10				MG-CR-18 Section 12	MG-CR-26	
	Section 17a[a]	Section 17b	Section 19	Section 21		Section 2b[b]	Section 7
Quartz	--	1	--	44	--	23	11
Hornblende	60	52	58	52	42	42	54
Biotite	2	1	21	--	--	3	--
Chlorite	6	10	18	--	36	2	2
Plagioclase	28	34	--	--	21	28	30
Microcline	--	1	--	--	--	--	--
Epidote	--	--	--	--	1	--	1
Magnetite	3	1	3	--	--	1	1
Pyrite	--	--	--	4	--	--	--
Sphene	1	Trace	--	--	--	1	Trace
Zircon	--	--	--	--	--	Trace	Trace
Apatite	--	--	--	--	--	Trace	Trace

[a] Section 17a is coarse-grained gneiss and 17b is schistose amphibolite.
[b] Section 2b is amphibolite at upper right in Figure 4.3. Rest of rock in this section is described under tonalites.

TABLE 4.7 BULK COMPOSITION OF TONALITES

Based on X-ray diffraction results.

Constituent	MG-CR-2A Section 9a	MG-CR-10 Section 6	MG-CR-18 Section 16	MG-CR-18 Section 17	MG-CR-26 Section 2a	MG-CR-26 Section 10	MG-CR-28 Section 3a	MG-CR-28 Section 3b	MG-CR-28 Section 13a	MG-CR-28 Section 13b	MG-CR-54 Section 16
Quartz	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant
Plagioclase	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant
Microcline	--	--	Abundant	Minor	--	--	--	--	--	--	--
Biotite	Minor	Trace	Minor	Trace	Abundant	Abundant	Trace	Minor	Abundant	Abundant	--
Chlorite	Minor	Abundant	Minor	Abundant	--	Trace	Minor	Trace	Trace	--	Minor
Hornblende	--	--	--	--	--	--	Trace	--	Abundant	--	--
Epidote	--	--	--	Trace	--	Trace	--	--	--	--	--
Magnetite	--	Trace	--	--	Trace	Trace	Trace	Trace	Trace	--	--
Hematite	--	Trace	--	--	Trace	--	--	--	--	Trace	--
Calcite	--	--	Trace	--	Trace	--	--	Trace	--	Trace	Trace
Clay	--	--	--	--	--	--	--	Trace	--	--	--

TABLE 4.8 BULK COMPOSITION OF GRANITES AND RHYOLITE

Based on X-ray diffraction results.

Constituent	Granites			Rhyolite
	MG-CR-2A Section 20	MG-CR-10 Section 13	MG-CR-18 Section 9	MG-CR-10 Section 7b
Quartz	Abundant	Abundant	Abundant	Abundant
Microcline	Abundant	Abundant	Abundant	Abundant
Plagioclase	Abundant	Abundant	Abundant	Abundant
Biotite	Minor	--	Trace	--
Chlorite	Minor	Trace	Minor	Abundant
Magnetite	Trace	--	Trace	--
Hematite	--	Minor	--	Minor
Epidote	--	--	Trace	--

TABLE 4.9 BULK COMPOSITION OF AMPHIBOLITES

Based on X-ray diffraction results.

Constituent	MG-CR-10				MG-CR-18	MG-CR-26	
	Section 17a	Section 17b	Section 19	Section 21	Section 12	Section 2b	Sections 7a and 7b
Quartz	--	Trace	--	Abundant	--	Abundant	Abundant
Hornblende	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant
Plagioclase	Abundant	Abundant	--	--	Abundant	Abundant	Abundant
Microcline	--	Trace	--	--	--	--	--
Biotite	Minor	Trace	Abundant	--	--	Trace	--
Chlorite	Minor	Minor	Abundant	--	Trace	--	Trace
Magnetite	--	--	--	--	Trace	Trace	--
Hematite	--	--	--	--	--	Trace	Trace
Clay	--	--	--	--	--	Trace	--
Pyrite	--	--	--	Minor	--	--	--

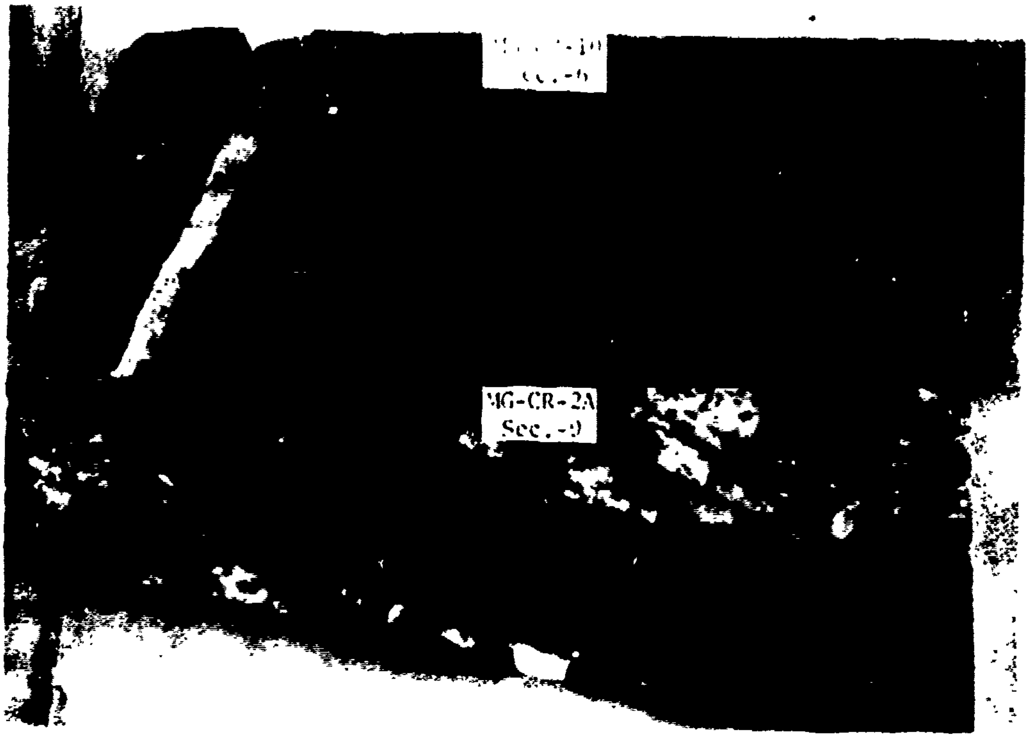


Figure 4.1 Tonalite, Cores MG-CR-10, Section 6, and MG-CR-2A, Section 9. MG-CR-10, Section 6, shows severely sheared texture. To the left is a calcite and quartz vein and in the center the narrow white lines are fractures. MG-CR-2A, Section 9, shows a biotite schist band in a coarse-grained tonalite; these rock types were not found in the rest of this core.

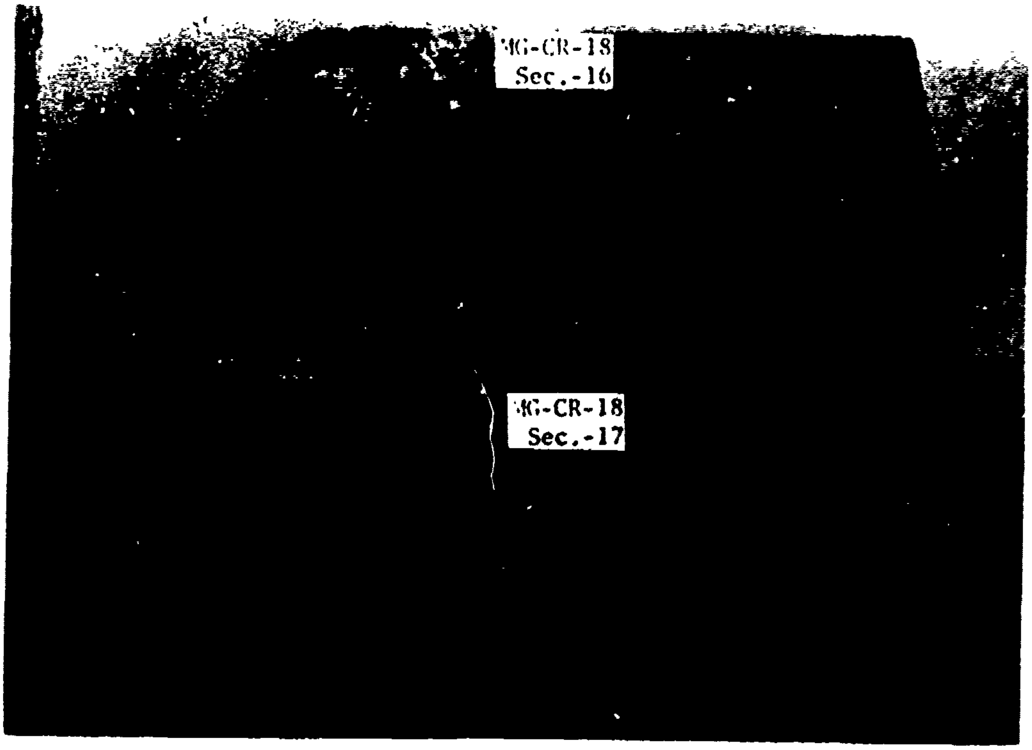


Figure 4.2 Tonalite, Core MG-CR-18, Sections 16 and 17. MG-CR-18, Section 16, shows a variation in texture from coarse to fine grained and many fractures. There was no compositional difference between the coarse- and fine-grained areas. MG-CR-18, Section 17, shows the extensive deformation of the section of this core. Note the variation in grain size and amount of dark minerals. Narrow light lines to the right are fractures.

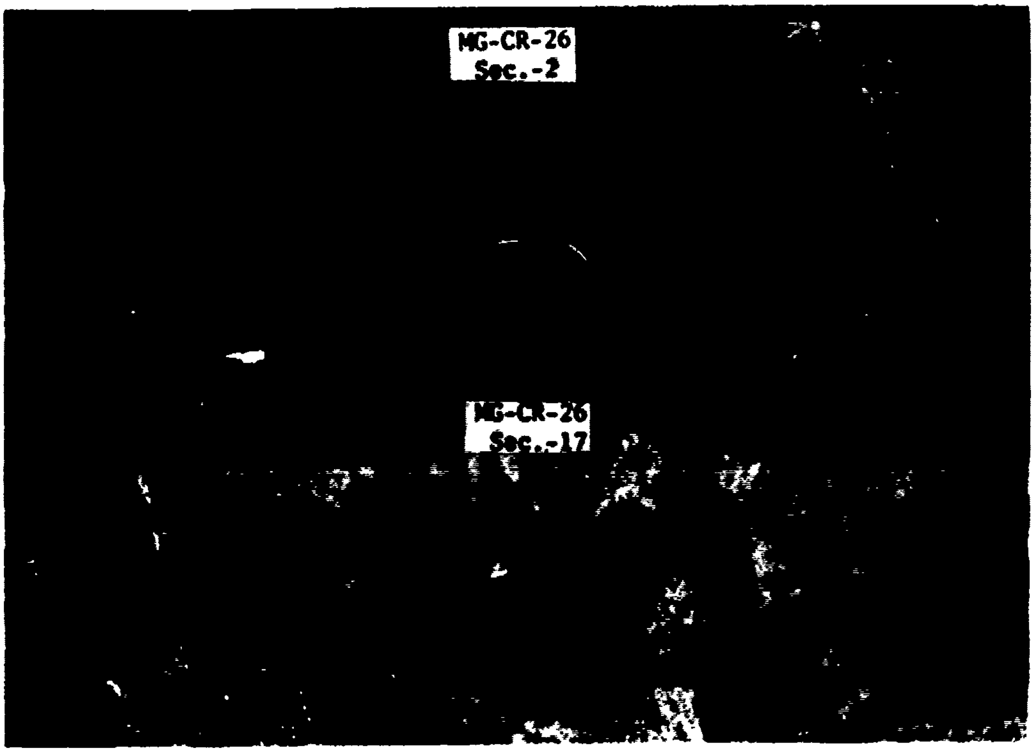


Figure 4.3 Tonalite, Core MG-CR-26, Section 2, and amphibolite, Core MG-CR-26, Section 17. MG-CR-26, Section 2, shows disrupted foliation and medium-grained textures of this gneiss. Dark rock at upper right is amphibolite. MG-CR-26, Section 17, shows contact between the dark biotite gneiss and light coarse-grained pegmatite.

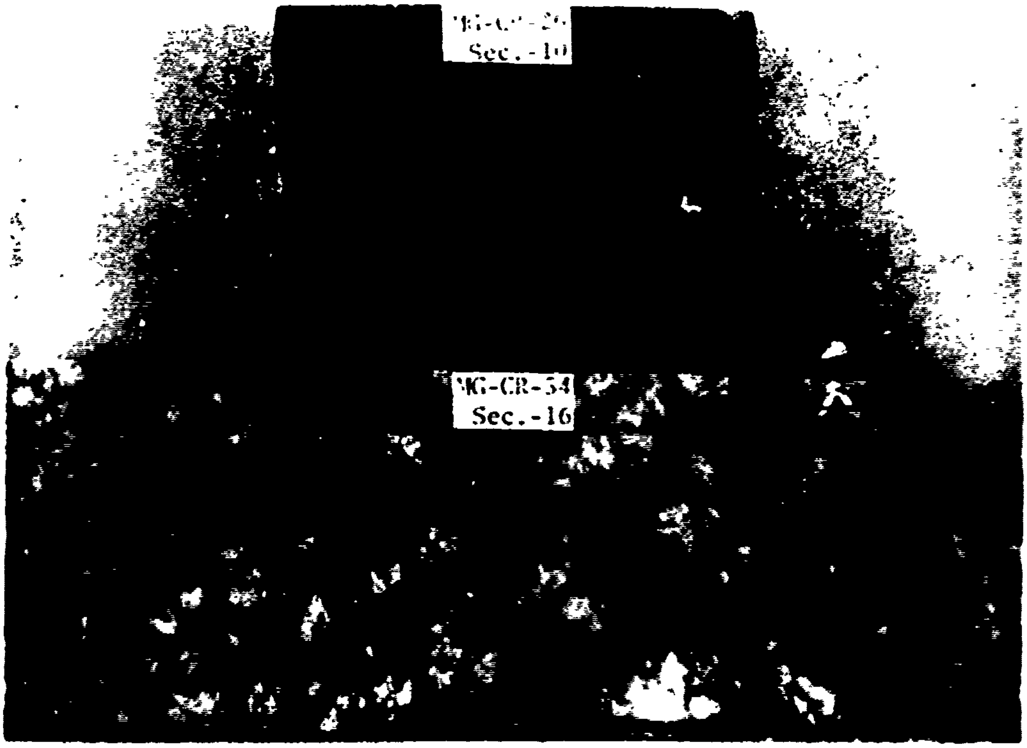


Figure 4.4 Tonalite, Cores MG-CR-26, Section 10, and MG-CR-54, Section 16. MG-CR-26, Section 10, shows fine-grained texture caused by shearing. Small light line to the right of the label is a low-angle fracture. MG-CR-54, Section 16, shows the typical severely fractured texture of the tonalites in Hole MG-CR-54.

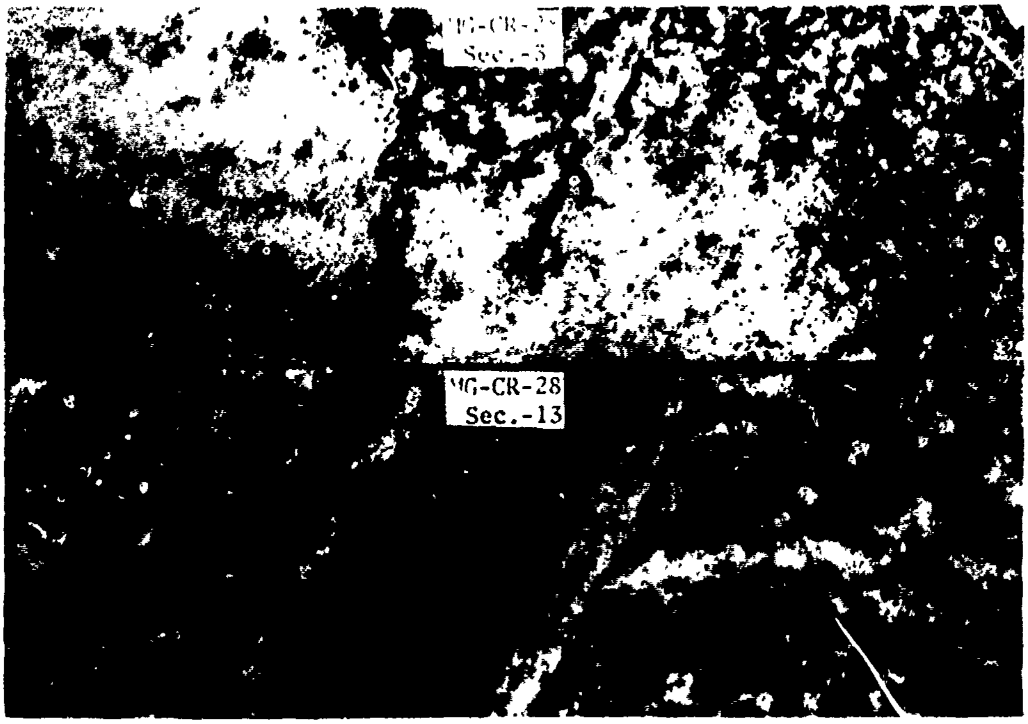


Figure 4.5 Tonalite, Core MG-CR-28, Sections 3 and 13. MG-CR-28, Section 3, shows a disrupted pegmatite (white area) in the tonalite. The center of the core was faulted and folded. MG-CR-28, Section 13, contains a well-foliated fine-grained band of gneiss. The foliation of the gneiss to the left of the band is parallel to the foliation of the band, but the foliation of the gneiss to the right of the band is almost perpendicular to that of the band and remaining gneiss.

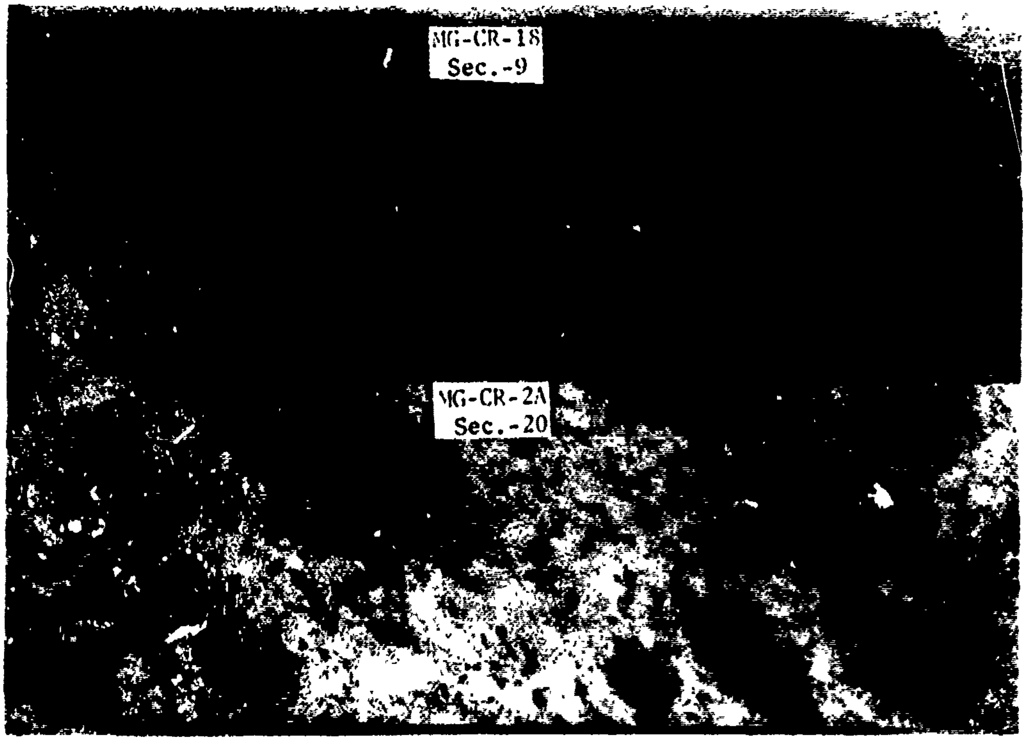


Figure 4.6 Granite, Cores MG-CR-18, Section 9, and MG-CR-2A, Section 20. MG-CR-18, Section 9, shows fine-grained texture and lack of structure typical of the granites in Core MG-CR-18. MG-CR-2A, Section 20, shows the poorly developed foliation in the granites of Core MG-CR-2A. Clots of biotite form the irregular bands.

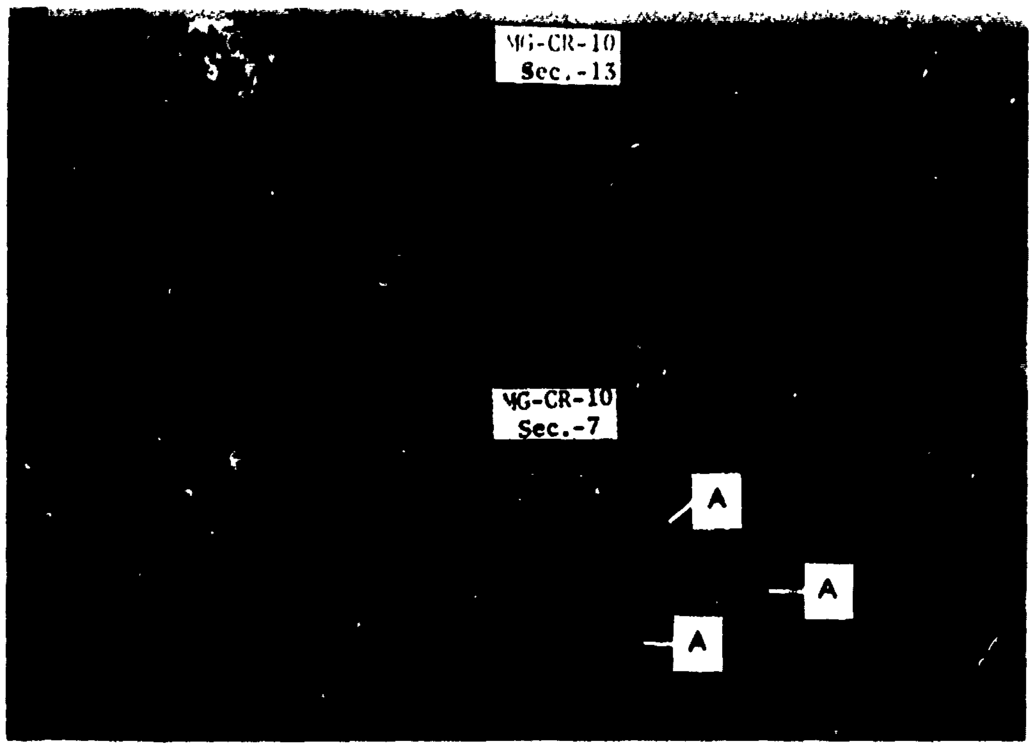


Figure 4.7 Granite, Core MG-CR-10, Section 13, and rhyolite, Core MG-CR-10, Section 7. MG-CR-10, Section 13, shows the typical sheared nature of the granites of Core MG-CR-10. Dark color of the section is due to a large amount of iron stain. MG-CR-10, Section 7, shows the only volcanic rock found in these cores. The very fine-grained band with several inclusions is a rhyolitic rock that has intruded a chlorite schist. The small circles (A) may be devitrified amygdules.

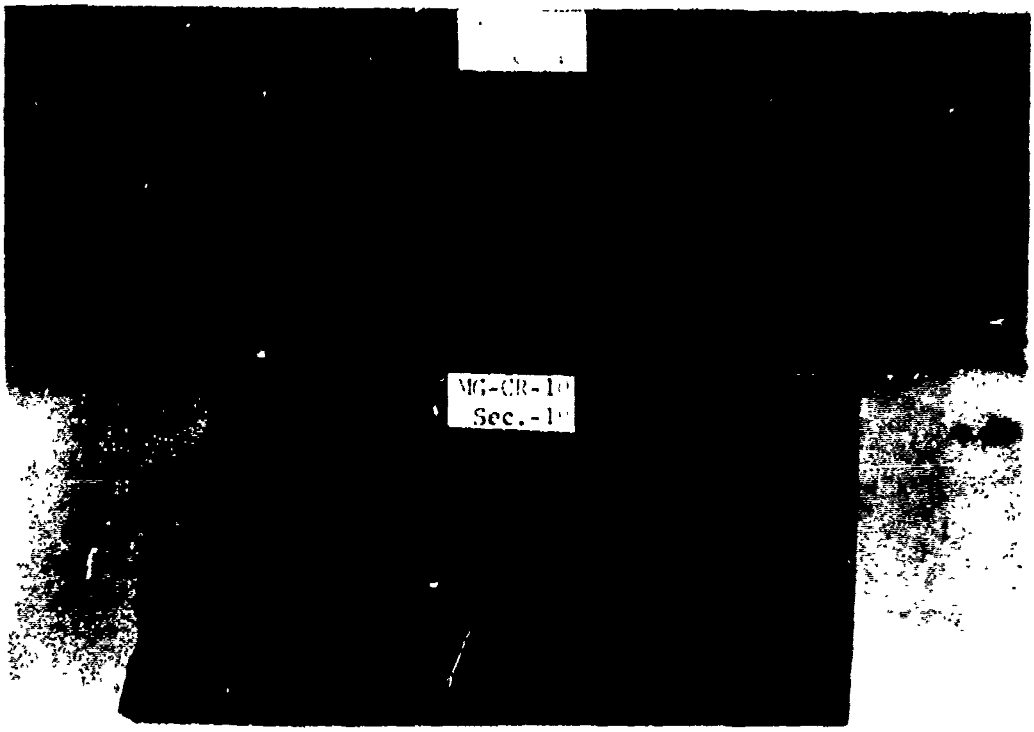


Figure 4.8 Amphibolite, Core MG-CR-10, Sections 17 and 19. MG-CR-10, Section 17, shows a contact between a gneissic amphibolite (17a) (top) and a schistose amphibolite (17b) (bottom). The rocks have similar compositions. Small white lines cutting both rocks are sealed fractures. MG-CR-10, Section 19, shows a well-developed schistose structure which was not common in most of the amphibolites.

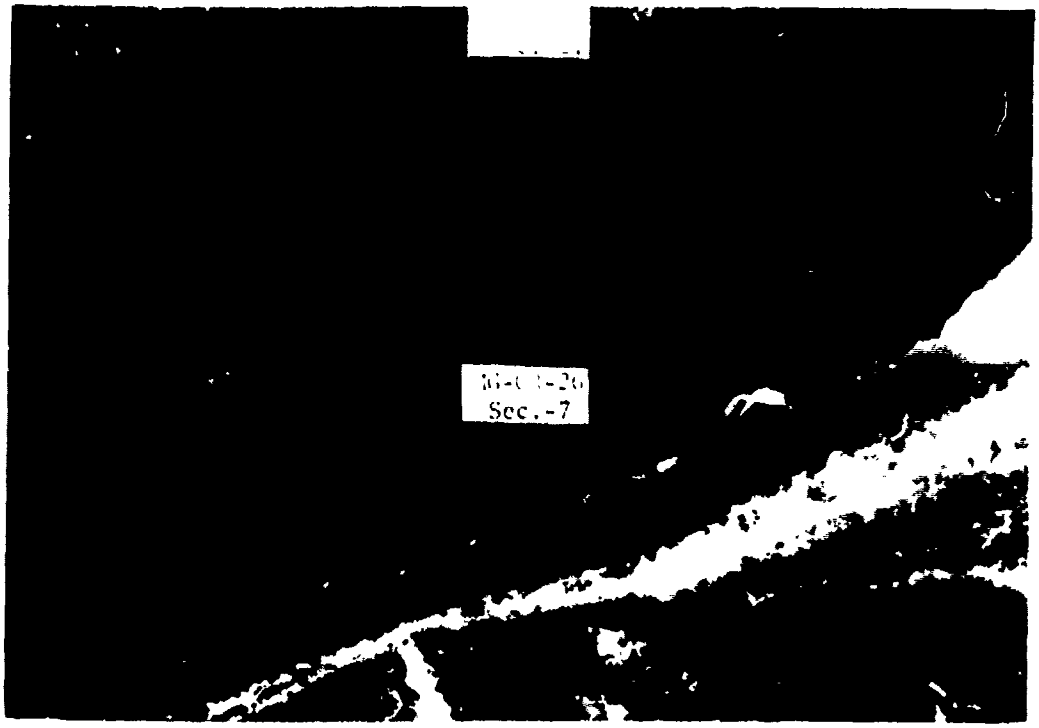


Figure 4.9 Amphibolite, Cores MG-CR-10, Section 21, and MG-CR-26, Section 7. MG-CR-10, Section 21, shows many fractures and a poorly developed banding caused by mineral segregation. MG-CR-26, Section 7, shows coarse-grained amphibolite cut by a quartz band.

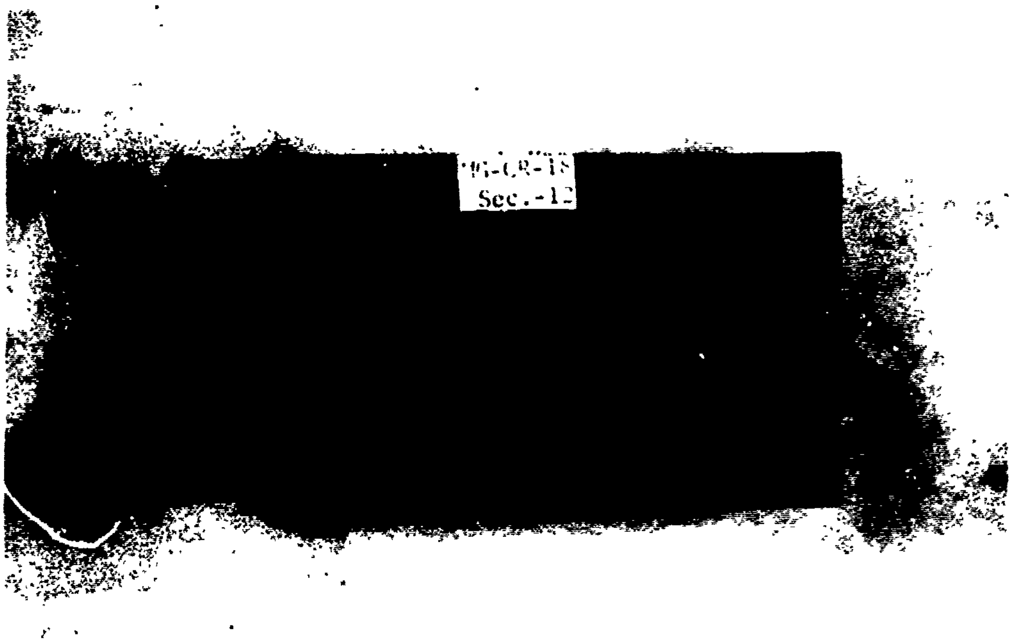


Figure 4.10 Amphibolite, Core MG-CR-18, Section 12. This section shows fine-grained amphibolite with several sealed fractures (light lines).

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1 DISCUSSION

The nature of the objective of these rock quality tests dictates overall evaluation of the core on a hole-to-hole basis. In the instances where individual holes yielded core of only one rock type, the evaluation of the hole will, of course, be dictated by the characteristics of the particular rock type present. In those instances, however, where several rock types are represented in a single hole, the evaluation of the hole will necessarily reflect the quality of the least competent material tested.

To facilitate evaluation of the Michigamme study area in this manner, a rock quality chart (Figure 5.1) was prepared. Ultimate uniaxial compressive strengths depicted on this chart were expressed in one of three categories: good (above 12,000 psi), marginal (8,000 to 12,000 psi), and poor (less than 8,000 psi). Locations of the individual drill holes are shown in Figure 5.2.

5.2 CONCLUSIONS

On the basis of physical test results exhibited by the specimens of rock core received from the Michigamme study area, the following conclusions appear to be justified:

1. The rock core received from the Michigamme study area was

petrographically identified as predominately tonalite, potash granite, and amphibolite with relatively minor amounts of biotite schist and pegmatite.

2. Most specimens contained fractures which ranged in orientation from horizontal to vertical. Several specimens contained well-developed systems of fracture.

3. The moderately fractured and intact tonalites from this area were found to range from relatively competent to very competent in quality, ultimate uniaxial compressive strengths ranging from 18,000 to 42,000 psi. A moderate degree of fracturing appeared to reduce the ultimate strength to approximately 70 percent of the ultimate for the intact tonalite. The critically to highly fractured tonalite was found to have been severely weakened by fracturing, generally to the extent that it was judged to be very incompetent material. Thus, this material should probably be considered the primary signal of incompetency in the Michigamme area.

4. Very similar to the tonalite discussed above, the moderately fractured to intact potash granite from this area was also found to range in quality from relatively competent to very competent (intact), ultimate uniaxial compressive strengths ranging from 18,000 to 40,000 psi, respectively. The moderate degree of fracturing reduced ultimate strengths, on the average, to approximately 60 percent of the ultimate value exhibited by the intact granite. The effect of

the presence of fractures oriented at critical angles was even more pronounced, average ultimate strengths falling to approximately 30 percent of the magnitude yielded by the intact core. This large loss of strength was still, however, not great enough to warrant classifying the critically fractured granite as incompetent. The three potash granite specimens containing open fractures and/or vesicles exhibited physical properties characteristic of incompetent rock.

5. The amphibolite received from the Michigamme study area was, in most cases, found to be somewhat weaker than the tonalite and potash granite specimens in the same general state of fracture. The intact core was rather competent, exhibiting an average ultimate uniaxial compressive strength of approximately 27,000 psi. The moderately fractured core was relatively competent material, exhibiting an average ultimate strength approximately 60 percent as great as that yielded by the intact core. The critically to highly fractured amphibolite ranged in quality from incompetent to marginal, with ultimate strengths ranging from approximately 4,000 to 12,000 psi.

6. The pegmatite specimens received from this area were intact and very competent. Ultimate uniaxial compressive strengths averaged approximately 30,000 psi.

7. The biotite schist from the Michigamme study area was relatively competent material, exhibiting ultimate strengths which averaged approximately 21,000 psi.

8. Elastic constants determined on the moderately fractured and intact rock from this area were generally rather high with Young's modulus ranging from approximately 9 million to 15 million psi. Constants determined for critically to highly fractured core were slightly lower, while those computed for the vesicular granite specimens were, predictably, quite low.

9. The material from this area was generally quite brittle, exhibiting little hysteresis and no significant residual strain.

10. Three-directional velocity tests revealed the potash granites to be relatively isotropic. With two exceptions, the tonalites were also found to be rather isotropic. Two of the tonalites were, however, somewhat gneissic in texture, and exhibited considerably lower compressional wave velocities in the direction perpendicular to the banding (axial direction). These low velocities resulted in rather high deviations from the average compressional wave velocity (5.0 and 9.1 percent), and in classifying the banded gneissic tonalite as relatively anisotropic.

11. Tensile strengths were rather high, with indirect (Brazilian) strengths generally found to be somewhat higher than the corresponding direct strengths. The direct strengths should, however, be more representative of the true tensile strength since the direct test allows, to a much greater degree, rock failure at the point of minimum strength.

Evaluation on a hole-to-hole basis indicates the potash granite removed from Hole MG-CR-2A and the gneissic tonalite and amphibolite removed from Holes MG-CR-26 and -28 to be relatively competent to very competent rock. These holes represent materials which should offer good possibilities as competent, hard rock media.

Hole MG-CR-18 yielded specimens of potash granite, tonalite, and amphibolite. This variety of materials exhibited physical characteristics generally representative of marginal to good quality rock, and should offer some possibility as a competent hard rock medium, provided the single zone of incompetent rock is not a disqualifying factor. The tonalites, amphibolites, and potash granites representative of Holes MG-CR-10 and -54 were generally fractured and exhibited physical characteristics typical of rock of lower quality than that required of competent media.

The above evaluations have been based on somewhat limited data, and, therefore, more extensive investigation will be required in order to fully define the individual areas under consideration.

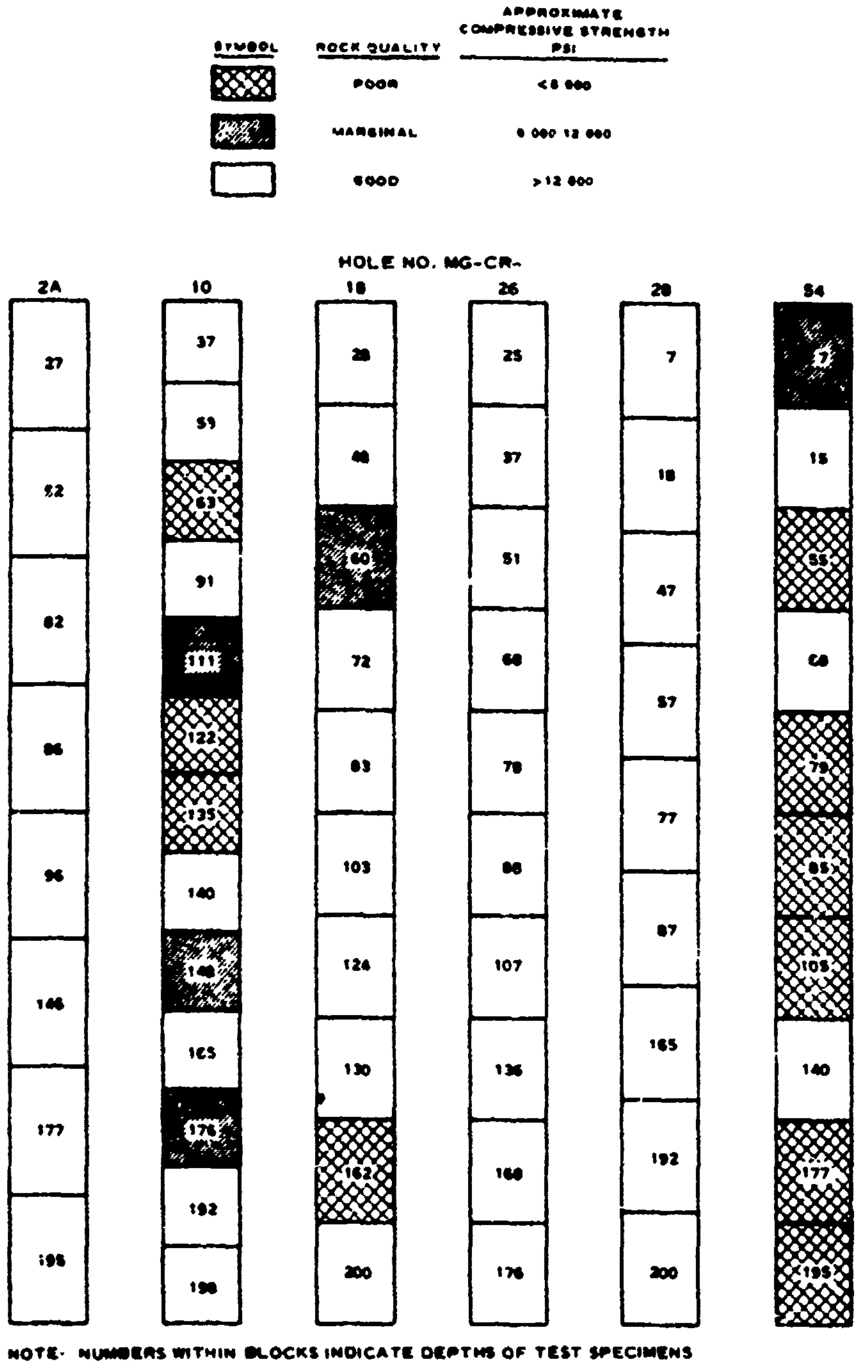


Figure 5.1 Depth versus quality as indicated by compressive strength for individual holes.

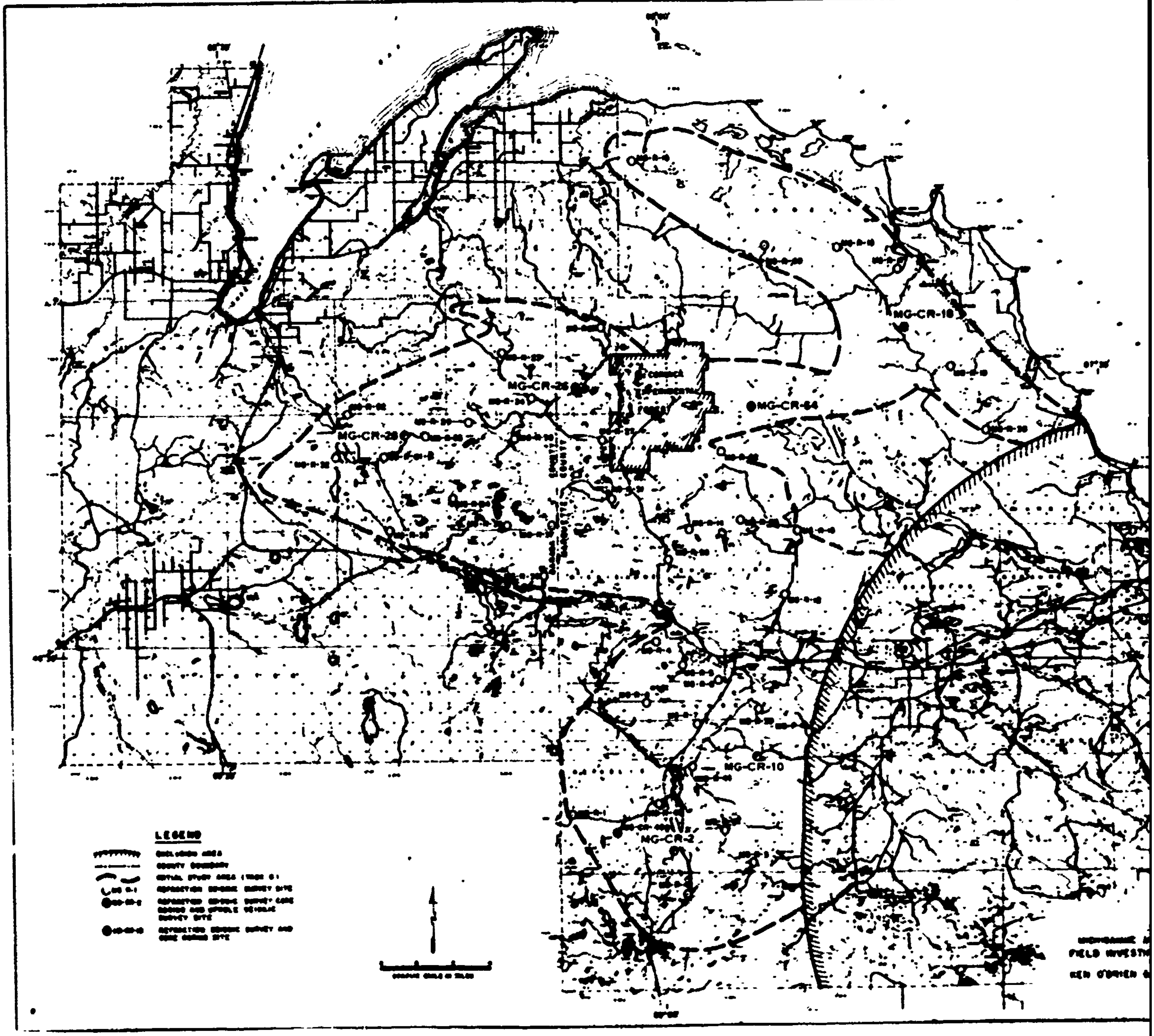


Figure 5.2 Location of drill holes.

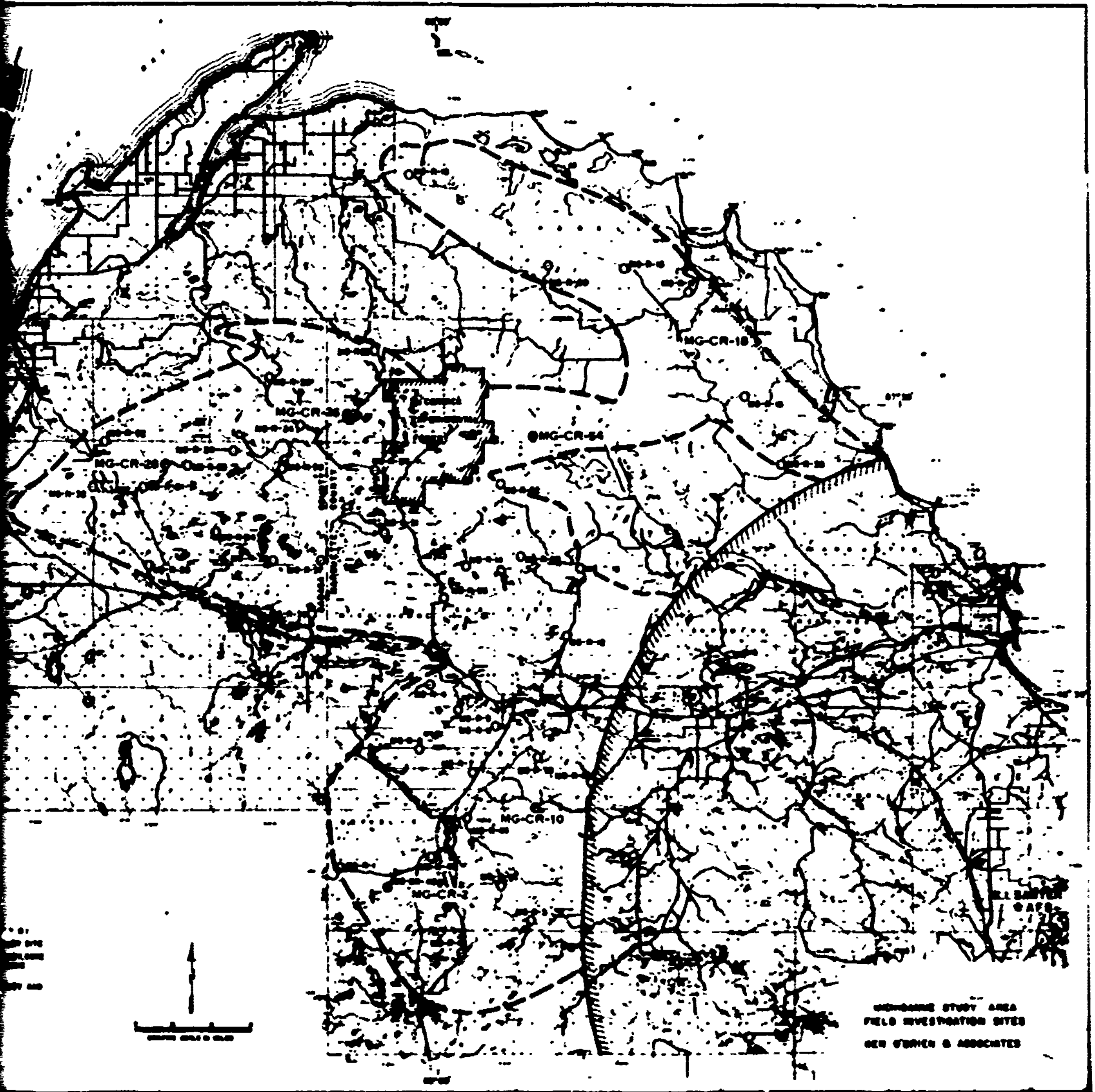


Figure 5.2 Location of drill holes.

APPENDIX A

DATA REPORT

Hole MG-CR-2A

12 September 1969

Hole Location: Marquette County, Michigan

Longitude: 87° 59' 23" West

Latitude: 46° 21' 08" North

Township 46N, Range 29W, Section 30, NW 1/4 SW 1/4

Core

1. The following core was received on 8 September 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	27
2	33
3	42
4	52
5	62
6	72
7	82
8	86
9	96
10	105
11	115
12	125
13	135
14	145
15	150
16	157
17	165
18	177
19	187
20	195

Description

2. The samples received were predominantly light- to pink-colored rock identified as coarse-grained granite by the field log received with the core. Piece Nos. 8 and 18 were identified as amphibolite and piece Nos. 1 and 9 as granite-amphibolite combinations.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below:

Sample No.	Description	Core Depth	Sp Gr	Schmidt No.	Comp Strg, psi	Comp Wave Vel, fps
1	Intact, Granite Biotite Schist	27	2.788	--	18,030	19,480
4	Intact, Granite	52	2.629	51.9	40,910	19,180
7	Intact, Granite	82	2.613	53.5	39,090	19,510
8	Intact, Biotite Schist	86	2.953	50.0	20,450	21,740
9	Intact, Granite Biotite Schist	96	2.719	--	20,150	18,560
14	Intact, Granite	145	2.640	50.9	31,820	18,360
18	Intact, Biotite Schist	177	2.964	49.5	26,060	21,720
20	Intact, Granite	195	2.628	55.2	34,850	18,960
Average Granite			2.628	52.9	36,670	21,280
Average Biotite Schist and Combination			2.856	49.8	21,170	23,870

The Schmidt hammer test was not conducted on the granite-amphibolite specimens due to possibility of breakage. Two distinct strength levels of rock are apparent, as given above, both representing very competent material. The biotite schist is a very dense rock with unusually high wave velocity. However, the granite yielded the higher compressive strength.

Moduli of deformation

4. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 14 and 19. Stress-strain curves are given in plates 1 and 2. Specimen 19 was cycled at 10,000 psi and specimen 14 at 20,000 psi. Results are given below.

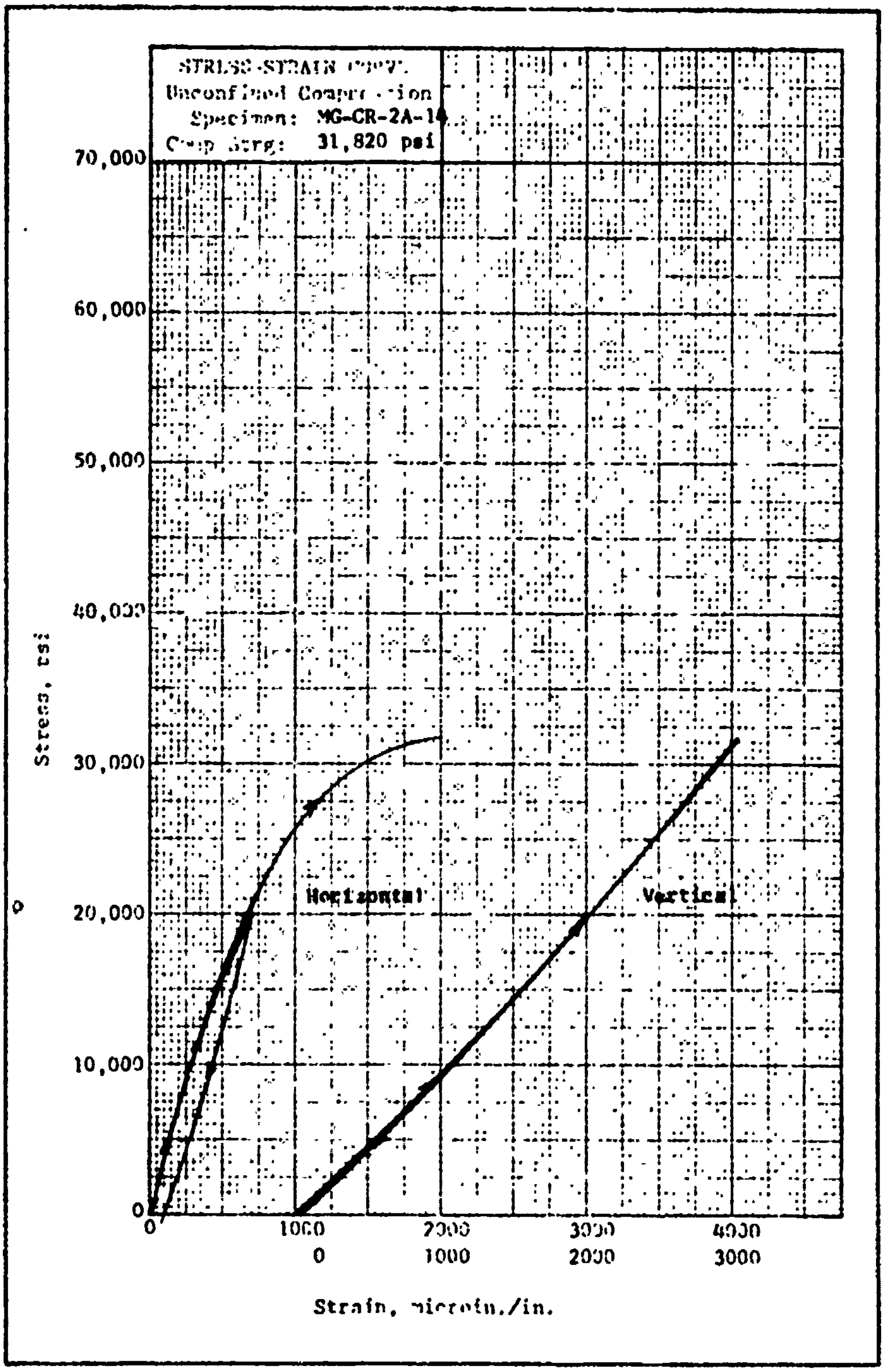
Specimen No.	Modulus, psi x 10^6 Young's	Modulus, psi x 10^6 Bulk	Modulus, psi x 10^6 Shear	Shear Velocity, fps	Poisson's Ratio
			Dynamic Tests		
14	10.1	6.6	4.1	10,690	0.24
19	15.6	10.5	6.2	12,490	0.25
			Static Tests		
14	10.7	5.9	4.5	--	0.20
19	14.9	9.9	5.9	--	0.25

All of the rock tested herein is apparently rather rigid material, exhibiting little hysteresis. Agreement between the different methods of moduli determination is exceptionally good.

Conclusions

5. The core received from hole MG-CR-2A was identified as predominantly pink granite by the field log received with the core. Several biotite schist and biotite schist granite combination specimens were also present. No macrofracturing was noted. Unconfined compressive tests indicated that all rock was very competent material; the granite somewhat the stronger, but the biotite schist the denser.

Property	Granite	Biotite Schist and Combination
Specific Gravity	2.628	2.856
Schmidt Number	52.9	49.8
Compressive Strength, psi	35,570	21,170
Compressional Wave Velocity, fps	21,280	23,870
Static Young's Modulus, psi x 10^{-6}	10.0	15.0



STRESS-STRAIN CURVE
Unconfined Compression
Specimen: MG-CR-2A-14
Comp Strg: 31,820 psi
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Stress, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE A1

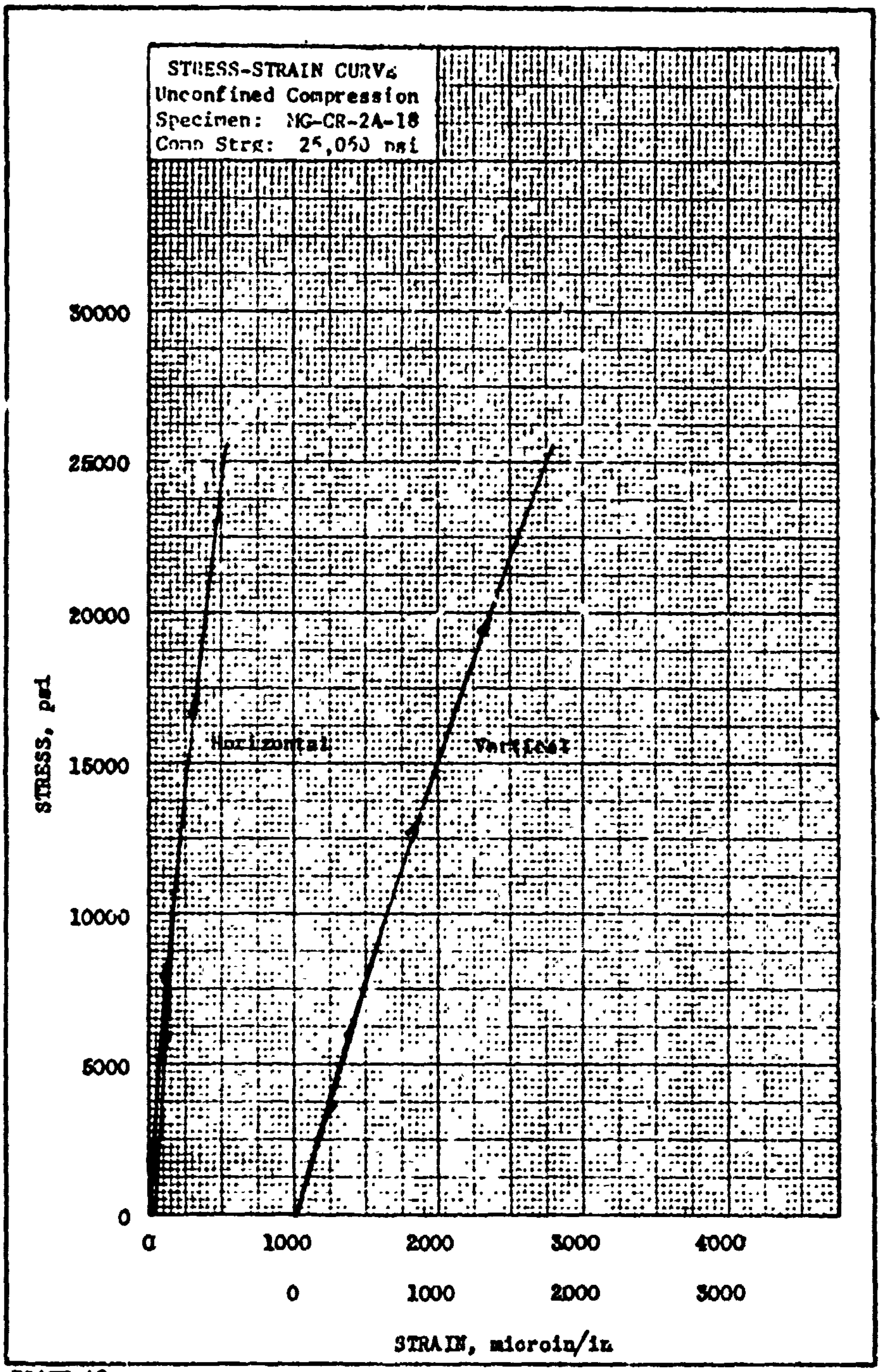

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: MG-CR-2A-18
Comp Strg: 25,050 psi
STRESS, psi
30000
25000
20000
15000
10000
5000
0
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE A2

APPENDIX B

DATA REPORT

Hole MG-CR-10

3 September 1969

Hole Location: Marquette County, Michigan

Longitude: 87° 53' 25" West

Latitude: 46° 25' 19" North

Township 47N, Range 29W, Section 35, SE 1/4

Core

1. The following core was received on 21 August 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	27
2	37
3	49
4	53
5	63
6	74
7	83
8	91
9	102
10	111
11	115
12	122
13	130
14	135
15	140
16	148
17	156
18	165
19	176
20	184
21	196
22	192
23	198

Description

2. The samples received were quite variable, generally identified as feldspathic porphyroblastic gneiss and schist and amphibolite by the field log received with the core. Piece Nos. 1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 14, 15, 16, 17, 18, 19, 22, and 23 contained fractures, most of which were healed.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below.

Sample No.	Rock Type	Description	Core Depth	Sp Gr	Schmidt No.*	Comp Strg psi	Comp Wave Vel fps
2	Tonalite	Vertical Fractures	37	2.711	--	26,540	18,925
4	Tonalite	Vertical Fractures	53	2.662	59.0	25,820	18,900
5	Tonalite	Critical Angle Fracture	63	2.659	55.9	7,700	17,160
8	Granite	Vertical and Critical Angle Fractures	91	2.661	57.1	14,090	19,080
10	Amphibolite	Highly Fractured	111	2.706	--	8,210	17,230
12	Granite	Vuggy, No Noticeable Fractures	122	2.494	28.3	7,820	18,805
14	Granite	Vuggy, Vertical Fracture	135	2.499	--	5,200	12,880
15	Amphibolite	Critical Angle Fracture	140	2.841	--	12,120	19,395
16	Amphibolite	Critical Angle Fracture	148	2.854	46.8	8,000	16,845
18	Tonalite	Vertical Fracturing	165	2.659	61.8	27,180	19,410
19	Amphibolite	Critical Angle Fractures	176	2.961	55.3	10,240	22,175
22	Amphibolite	Vertical Fractures	192	3.170	54.5	15,695	21,770
23	Tonalite	Vertical Fractures	198	2.677	61.2	29,240	17,350
Average of Vuggy Specimens (2)				2.496	28.3	6,510	15,840
Average of Specimens Containing Critical Angle Fractures (6)				2.780	53.8	10.060	18,645
Average of Specimens Containing Vertical Fractures (5)				2.776	59.1	24,895	19,270

* Schmidt hammer test not conducted on several specimens due to possibility of breakage.

Moduli of deformation

4. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 15, 16, and 22. Stress-strain curves are given in plates 1, 2, and 3. Specimens 15 and 22 were cycled at 10,000 psi. Results are given below.

Specimen No.	Modulus, psi x 10^6 Young's	Bulk	Shear	Shear Velocity, fps	Poisson's Ratio
		Dynamic Tests			
12	5.5	9.3	2.0	7,635	0.40
14	3.9	3.7	1.4	6,495	0.33
15	9.4	9.7	3.5	9,560	0.34
16	7.7	7.0	2.9	8,710	0.32
22	12.2	14.2	4.5	10,270	0.36
		Static Tests			
15	10.0	6.9	4.0	--	0.26
16	7.8	4.3	3.2	--	0.20
22	12.5	8.7	5.0	--	0.25

The three specimens tested statically, all very dense material, exhibited little hysteresis. Due to the voids, meaningful stress-strain data were not obtained on the vuggy specimens.

Conclusions

5. The core received for testing from hole MG-CR-10 was generally identified as feldspathic porphyroblastic gneiss and schist and amphibolite by the field log received with the core. The material from this hole was quite variable, as illustrated by the wide range of results obtained from the physical property tests. Generally, the vuggy material was rather weak, exhibiting an average compressive strength of 6510 psi. Specific gravities and compressional wave velocities were also quite low. The material containing critical angle fractures yielded an average compressive strength of 10,060 psi and an average compressional wave velocity of 18,545 fps. The material containing vertical fractures exhibited an average compressive strength of 24,895 psi. Vertical fracturing apparently had little effect on the strength; the majority of the failure modes in this group were either of a conical type or of a brittle, vertical splitting nature.

Property	Vuggy Specimens	Specimens with Critical Angle Fractures	Specimens with Vertical Fractures
Specific Gravity	2.495	2.780	2.776
Schmidt No.	28.3	53.6	59.1
Compressive Strength, psi	6,510	10,060	24,895
Compressional Wave Velocity, fps	15,940	18,545	19,270
Static Young's Modulus, psi x 10^{-6}	--	8.9	12.5

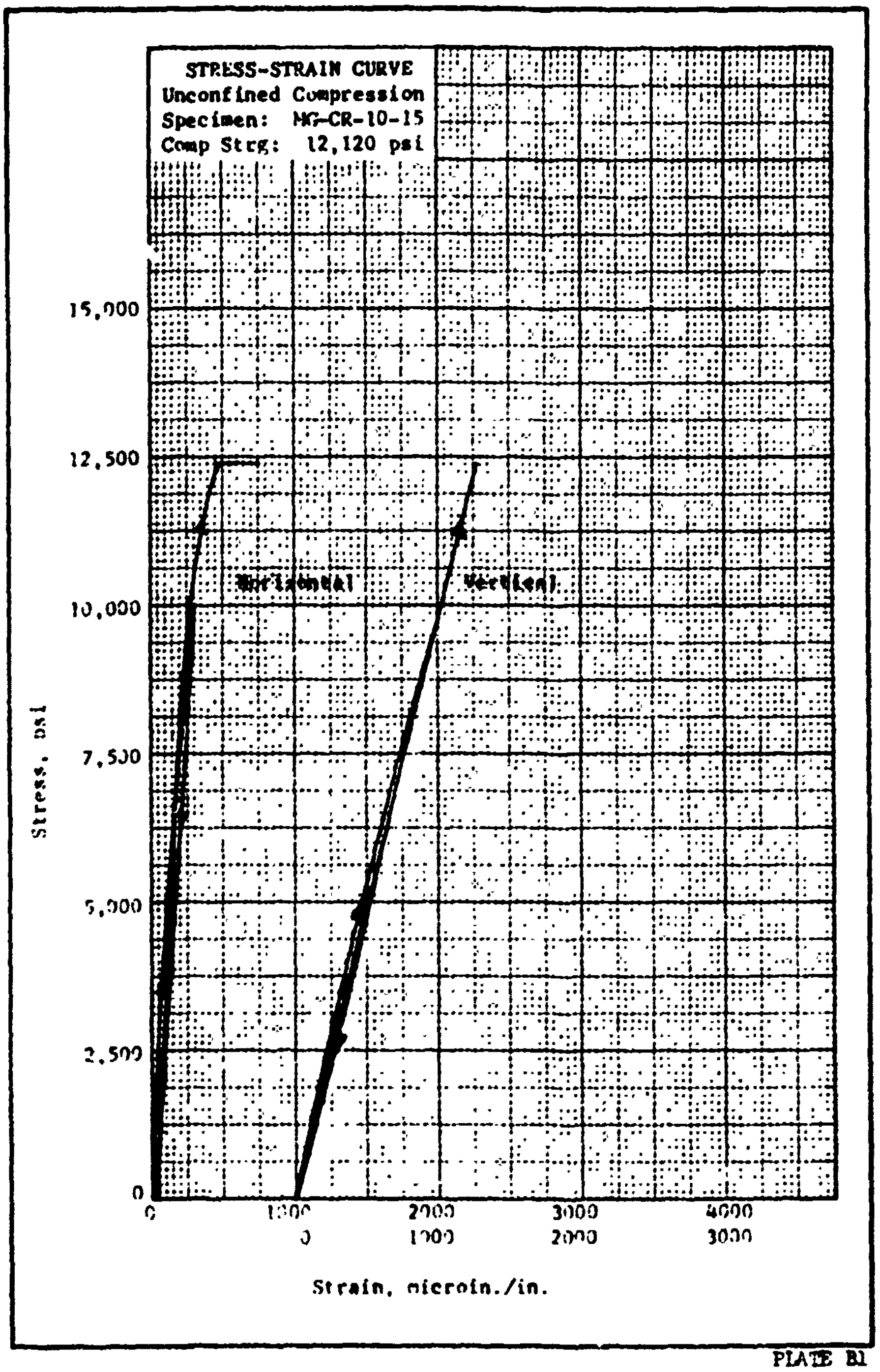

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: MG-CR-10-15
Comp Strg: 12,120 psi
Horizontal
Vertical
15,000
12,500
10,000
7,500
5,000
2,500
0
Stress, psi
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE B1

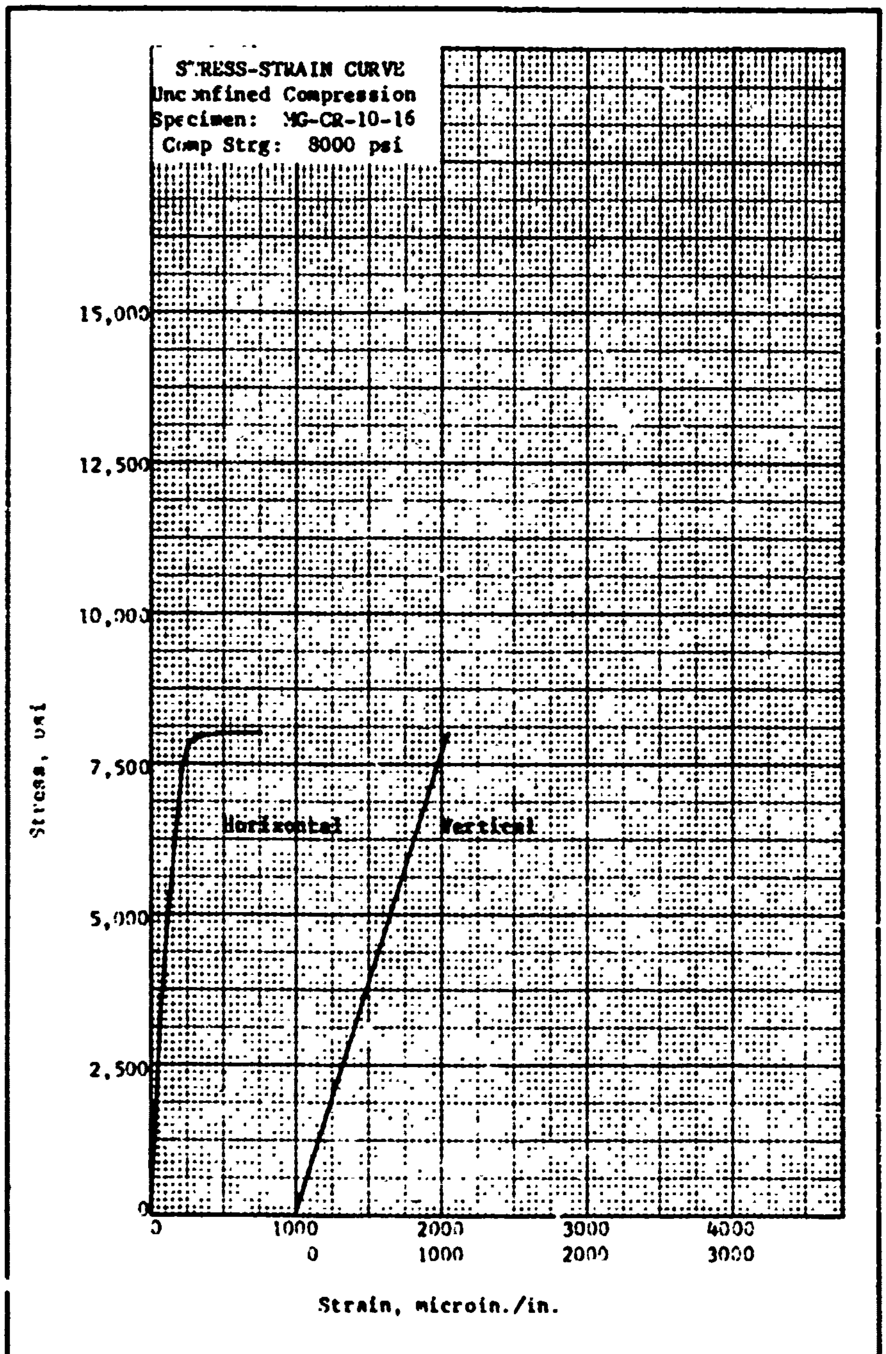

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: MG-CR-10-16
Comp Strg: 8000 psi
15,000
12,500
10,000
7,500
5,000
2,500
0
Stress, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE B2

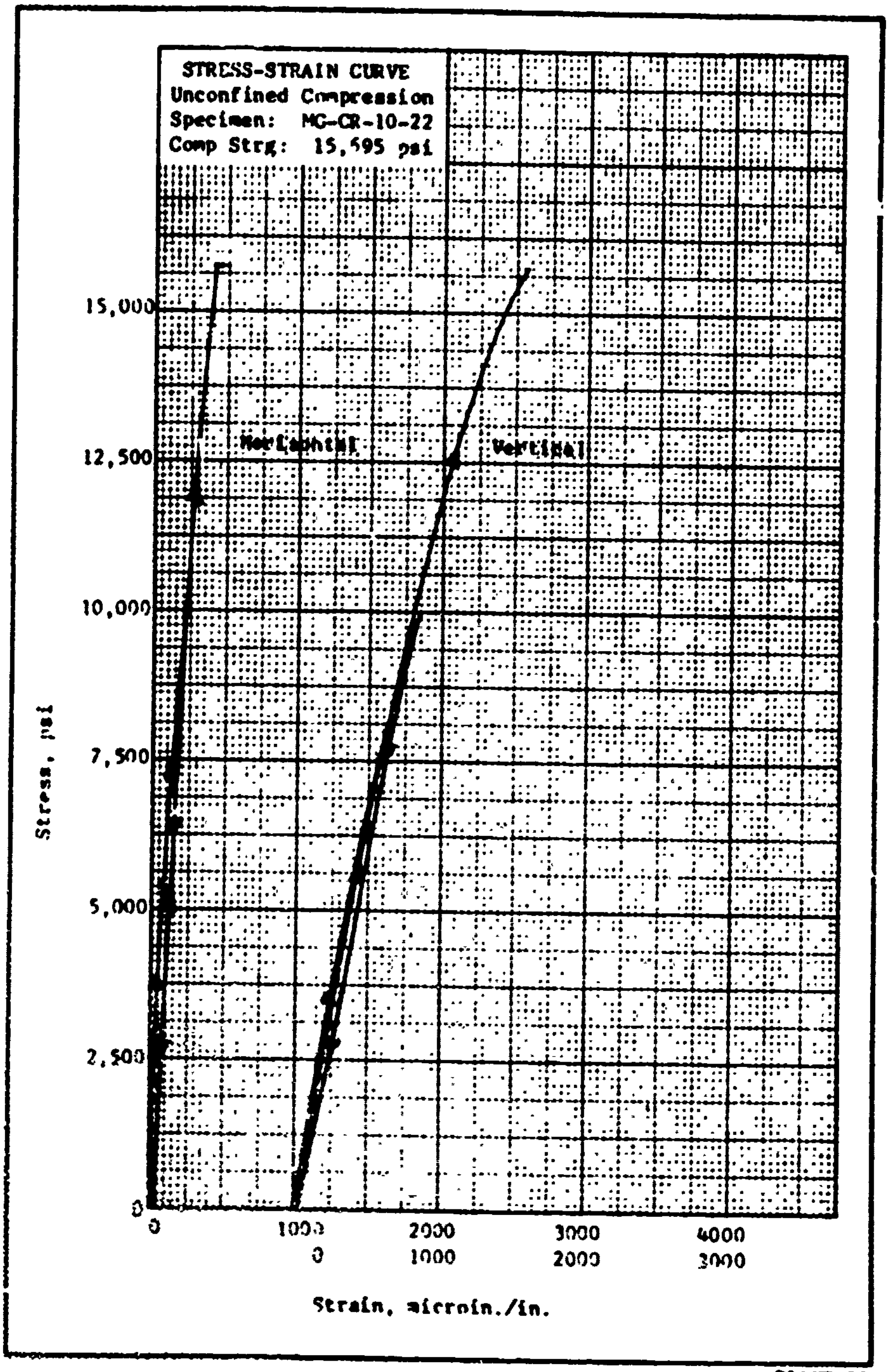

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: MG-CR-10-22
Comp Strg: 15,595 psi
Horizontal
Vertical
15,000
12,500
10,000
7,500
5,000
2,500
0
Stress, psi
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE B3

APPENDIX C

DATA REPORT

Hole MG-CR-1S

15 September 1969

Hole Location: Marquette County, Michigan

Longitude: 87° 43' 12" West

Latitude: 46° 44' 20" North

Township 50N, Range 27W, Section 7, SE 1/4 SE 1/4

Core

1. The following core was received on 11 September 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	29
2	37
3	48
4	60
5	72
6	83
7	93
8	103
9	113
10	120
11	124
12	130
13	141
14	151
15	162
16	171
17	182
18	193
19	200

Description

2. The samples received were pinkish- to gray-colored rock identified as granitic gneiss by the field log received with the core, except piece No. 12 which was identified as amphibolite. Practically all of the gneiss samples had tightly closed, sealed fractures. Only samples 13 and 15 contained seams and open fractures, i.e., fractures which have some visible, although discontinuous, void space between the contact surfaces.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below:

Sample No.	Description	Core Depth	Sp Gr	Schmidt No.	Comp Strg, psi	Comp Wave Vel, fps
1	Granite with Vertical Fractures	28	2.641	52.9	23,120	19,510
3	Granite with Vertical Fractures	48	2.685	52.0	30,310	19,580
4	Granite with Critically Oriented Fractures	60	2.667	37.4	11,090	17,540
5	Granite with Vertical Fractures	72	2.681	49.5	18,110	18,880
6	Granite with Critically Oriented Fractures	83	2.669	--	14,000	18,460
8	Granite with Vertical Fractures	103	2.654	51.4	18,210	19,440
11	Granite with Vertical Fractures	124	2.636	--	23,940	19,460
12	Moderately Fractured Amphibolite	130	2.988	45.6	15,850	21,520
15	Granite with Open Fractures	162	2.662	--	5,240	18,090
19	Moderately Fractured Amphibolite	200	2.853	42.6	13,330	20,740
Average (Except Specimen No. 15)			2.719	47.3	18,660	19,460

The Schmidt hammer test was not conducted on several specimens due to the possibility of breakage. Little or no effect of the tightly closed fractures is indicated on the physical test results. Where open fractures are present, strength will apparently be significantly reduced.

Moduli of deformation

4. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 3, 12, and 19. Stress-strain curves are given in plates 1, 2, and 3. Specimens 3 and 12 were cycled at 10,000 psi. Results are given below.

Specimen No.	Modulus, psi x 10^6 Young's	Bulk	Shear	Shear Velocity, fps	Poisson's Ratio
		Dynamic Tests			
3	11.9	7.4	4.9	11,600	0.23
12	14.5	11.0	5.9	11,870	0.28
19	13.5	9.3	5.4	11,880	0.25
		Static Tests			
3	11.3	6.5	4.7	--	0.21
12	13.4	7.9	5.5	--	0.22
19	10.5	7.0	4.2	--	0.25

The negligible hysteresis exhibited by the specimens which were cyclic stressed indicates a rather rigid material with tightly closed fractures.

Conclusions

5. The core received from hole MG-CR-18 was identified as predominantly granitic gneiss by the field log received with the core. Practically all samples contained very tightly closed fractures and contact surfaces. The

significant result was a very low compressive strength (5000 psi) obtained on one of two specimens found to have prominent macrofractures and seams. If such discontinuities are numerous in the cored mass, the conclusions on the area as a whole may be significantly affected.

Property	Results*
Specific Gravity	2.719
Schmidt Number	47.3
Compressive Strength, psi	18,660
Compressional Wave Velocity, fps	19,460
Static Young's Modulus, psi $\times 10^{-6}$	12.0

* Exclusive of low compressive strength obtained on fractured specimen.

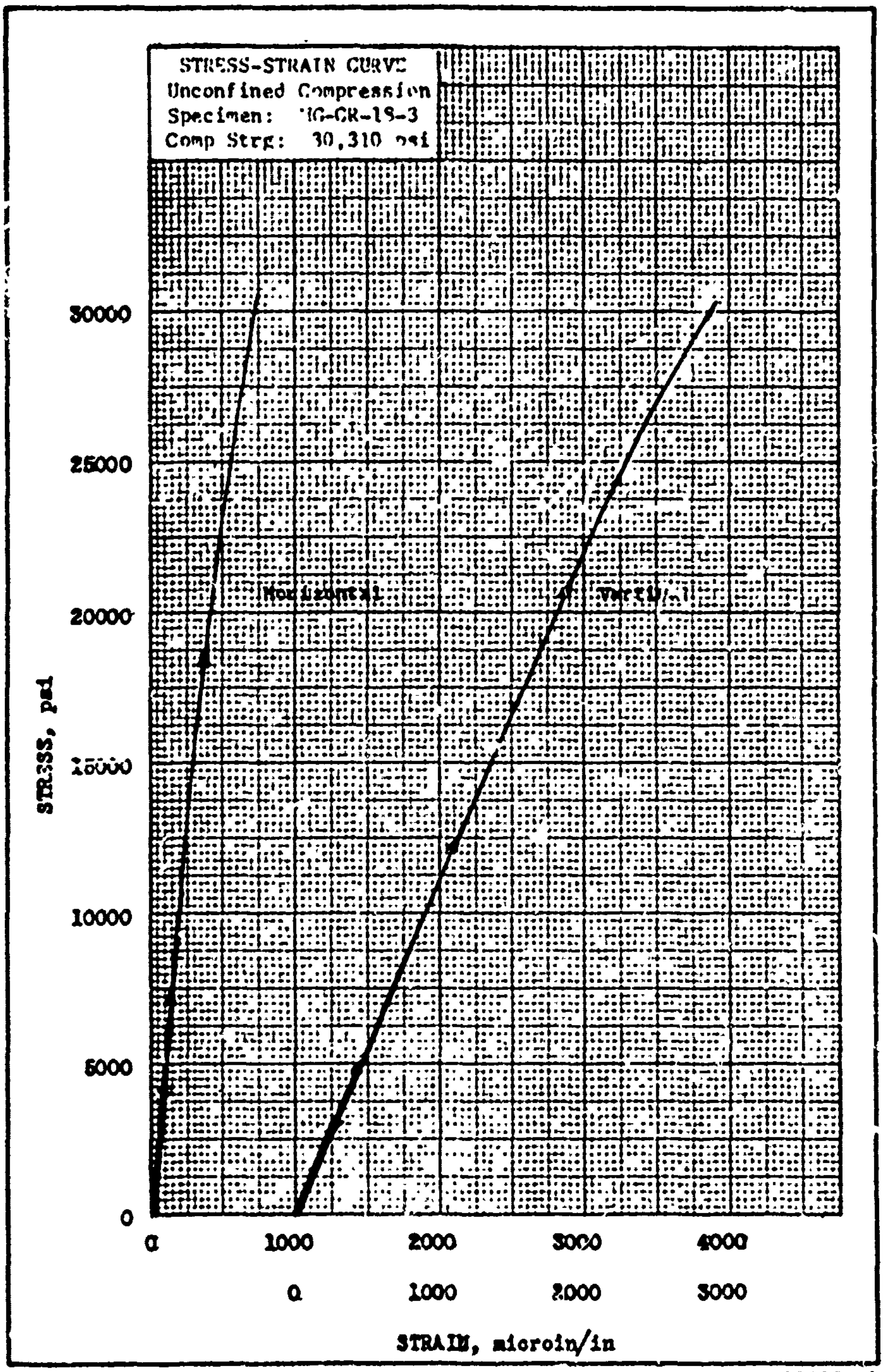
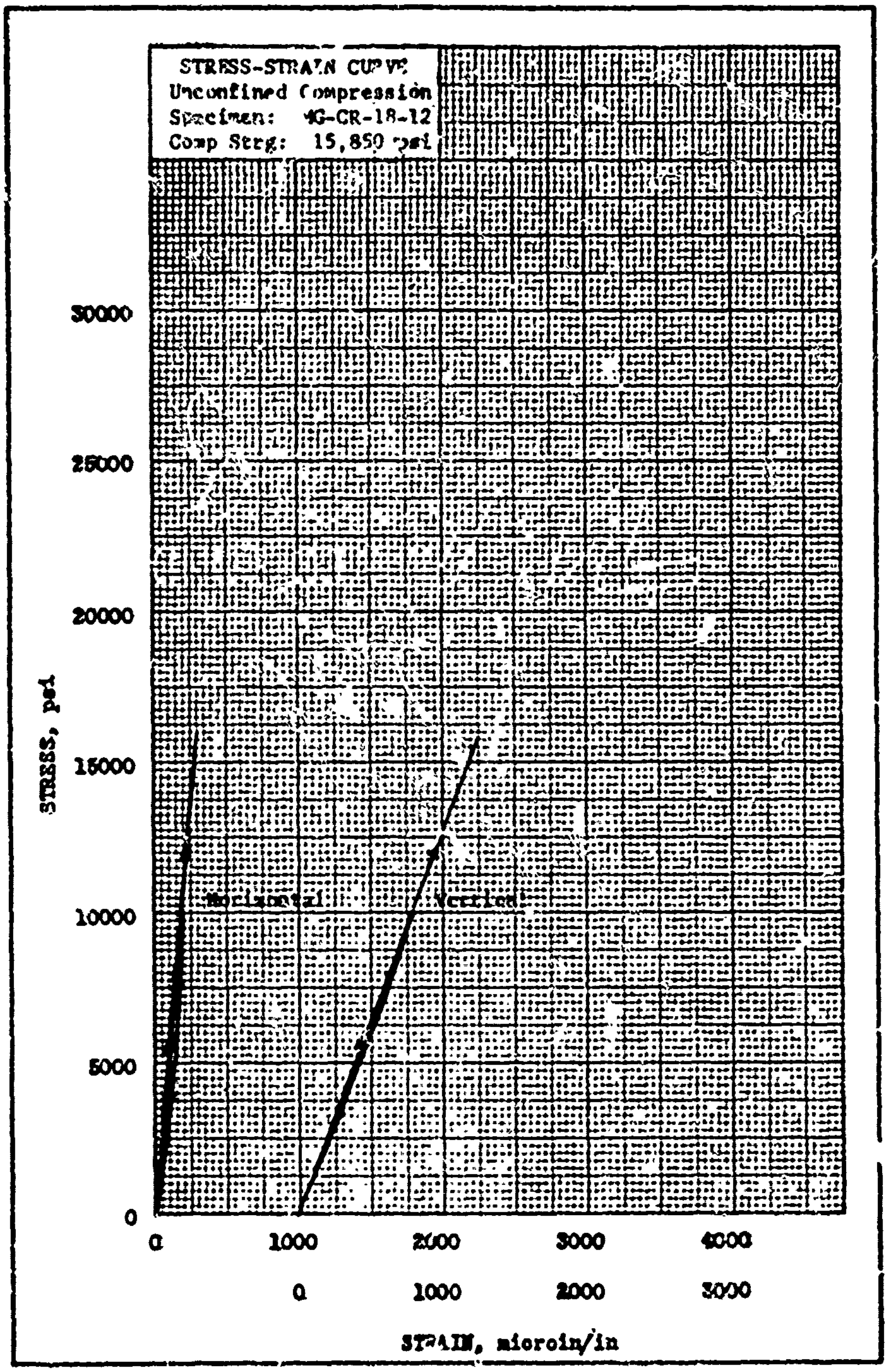

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: HG-CR-18-3
Comp Strg: 30,310 psi
Horizontal
Vertical
STRESS, psi
30000
25000
20000
15000
10000
5000
0
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE C1



STRESS-STRAIN CURVE
Unconfined Compression
Specimen: MG-CR-18-12
Comp Strg: 15,850 psi
STRESS, psi
30000
25000
20000
15000
10000
5000
0
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE C2

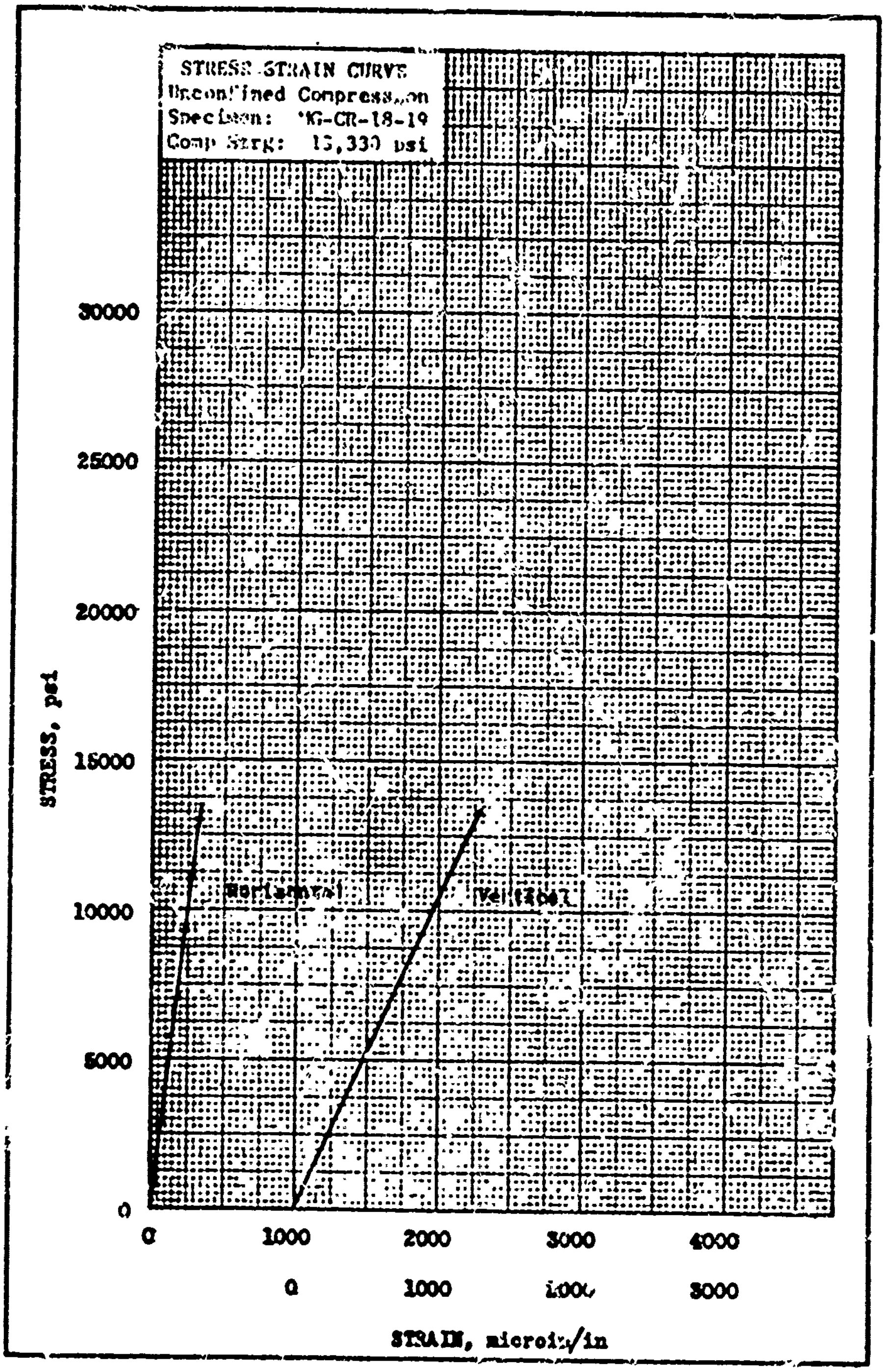

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: 'KG-CR-18-19
Comp Strg: 13,330 psi
30000
25000
20000
15000
10000
5000
0
STRESS, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE C3

APPENDIX D

DATA REPORT

Hole MG-CR-26

4 September 1969

Hole Location: Baraga County, Michigan

Longitude: 88° 05' 31" West

Latitude: 46° 41' 50" North

Township 50N, Range 30W, Section 29, SW 1/4

Core

1. The following core was received on 21 August 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	6
2	17
3	25
4	37
5	48
6	51
7	57
8	68
9	78
10	88
11	96
12	107
13	117
14	119
15	126
16	136
17	146
18	157
19	168
20	171
21	176
22	186
23	197
24	200

Description

2. The samples received were gray- to green-gray-colored rock identified as quartz-mica gneiss by the field log received with the core. Pegmatite dikes and intrusions were very abundant. Piece Nos. 5, 15, and 23 contained tightly closed fractures.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below:

Sample No.	Core Log Description	Core Depth	Sp Gr	Schmidt No.	Comp Strg, psi	Comp Wave Vel, fps
3	Amphibolite	25	2.997	58.8	25,200	21,955
4	Pegmatite	37	2.668	65.1	33,180	19,120
6	Vertical fractured tonalite	51	3.070	53.1	27,580	21,635
8	Tonalite	68	3.092	54.2	42,420	22,480
9	Amphibolite	73	2.840	56.2	29,240	20,415
10	Tonalite	88	2.779	61.5	38,940	19,345
12	Pegmatite	107	2.691	60.2	21,060	19,110
16	Moderately fractured amphibolite	136	2.891	54.1	17,730	20,810
19	Pegmatite	168	2.673	53.1	31,140	18,020
[illegible]	Amphibolite	176	2.760	61.2	25,900	19,355
Average Pegmatite Specimens (3)			2.677	59.5	28,460	18,750
Average Other Specimens (7)			2.918	57.0	29,590	20,855

The pronounced banding in the gneiss apparently did not adversely affect the physical test results.

Moduli of deformation

4. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the

proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 3, 4, and 10. Stress-strain curves are given in plates 1, 2, and 3. Specimens 4 and 10 were cycled at 20,000 psi; specimen 3 was cycled at 15,000 psi. Results are given below.

Specimen No.	Modulus, psi x 10^6 Young's	Bulk	Shear	Shear Velocity, fps	Poisson's Ratio
			Dynamic Tests		
3	14.7	11.8	5.7	11,875	0.29
4	9.3	8.4	3.5	9,895	0.31
10	10.7	8.5	4.2	10,540	0.29
			Static Tests		
3	13.9	9.2	5.5	--	0.25
4	11.0	7.0	4.4	--	0.24
10	10.8	7.5	4.3	--	0.25

All of the rock tested herein is apparently rather rigid material, exhibiting little hysteresis.

Conclusions

5. The core received for testing from hole MG-CR-25 was identified by the field log received with the core as gray to green-gray quartz-mica gneiss with abundant pegmatite dikes and intrusions. The only noticeable differences in physical properties between groups were the lower specific gravities and compressive wave velocities exhibited by

the pegmatite. Compressive strengths were somewhat variable, the average for all specimens tested being approximately 30,000 psi. Specimen No. 16 yielded the only compressive strength less than 20,000 psi. Modes of failure were generally of a conical or vertical splitting nature, apparently unaffected by banding.

Property	Average of Pegmatite Specimens	Average of Other Specimens
Specific Gravity	2.667	2.918
Schmidt No.	59.5	57.0
Compressive Strength, psi	28,450	29,590
Compressional Wave Velocity, fps	18,750	20,855
Static Young's Modulus, psi x 10^{-6}	11.0	12.3

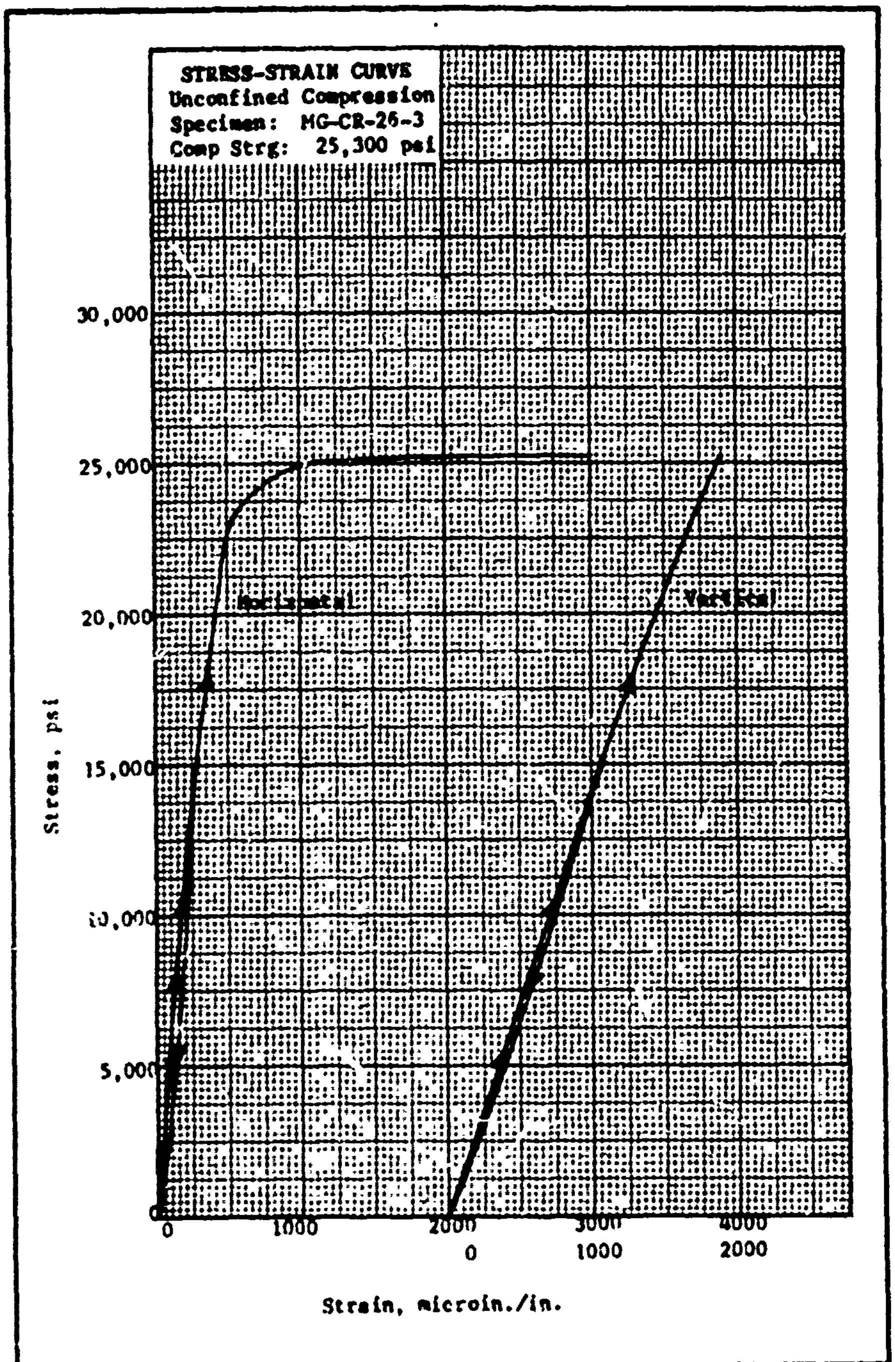

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: MG-CR-26-3
Comp Strg: 25,300 psi
Horizontal
Vertical
30,000
25,000
20,000
15,000
10,000
5,000
0
0
1000
2000
3000
4000
0
1000
2000
Stress, psi
Strain, microin./in.

PLATE D1

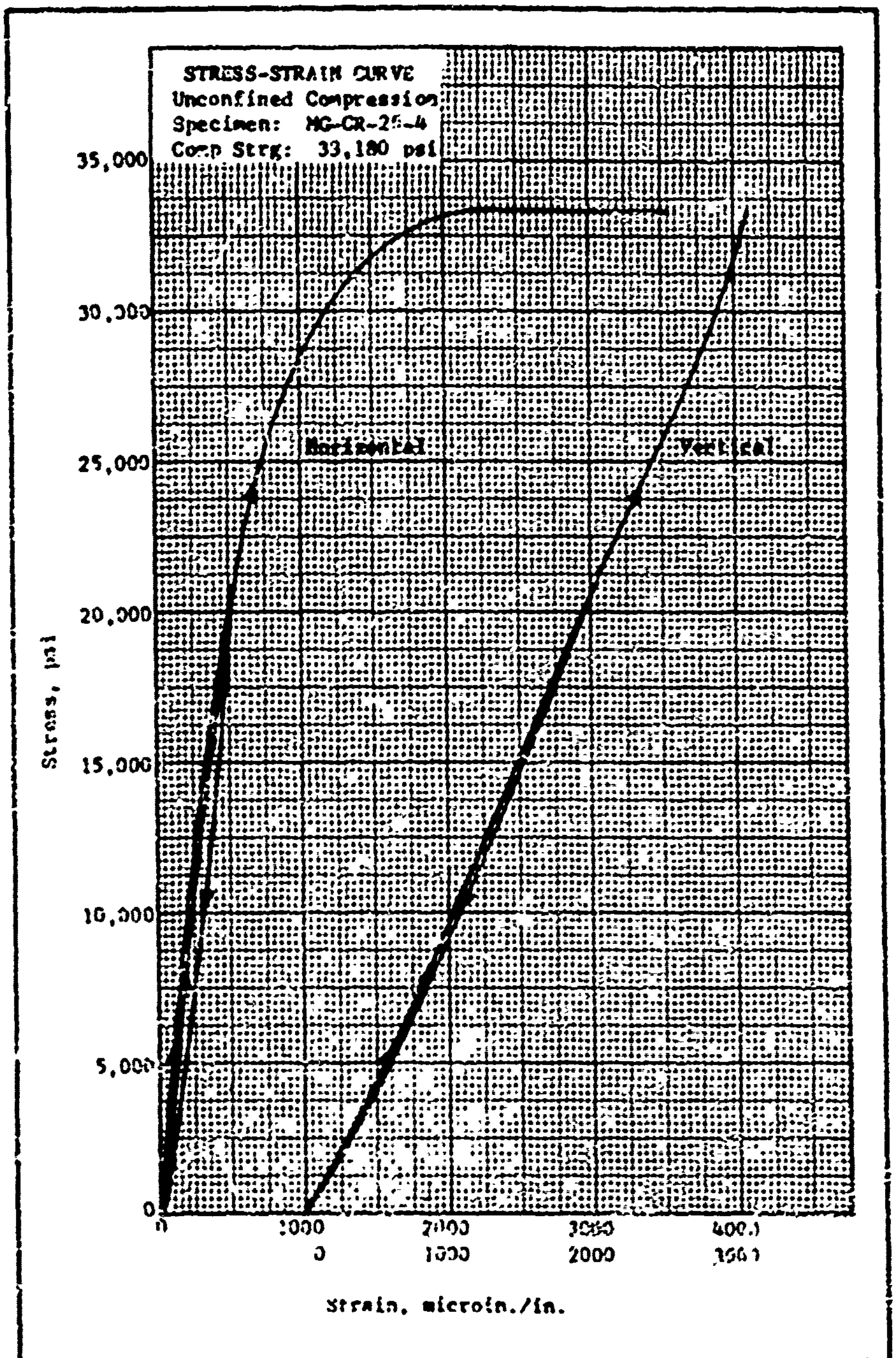
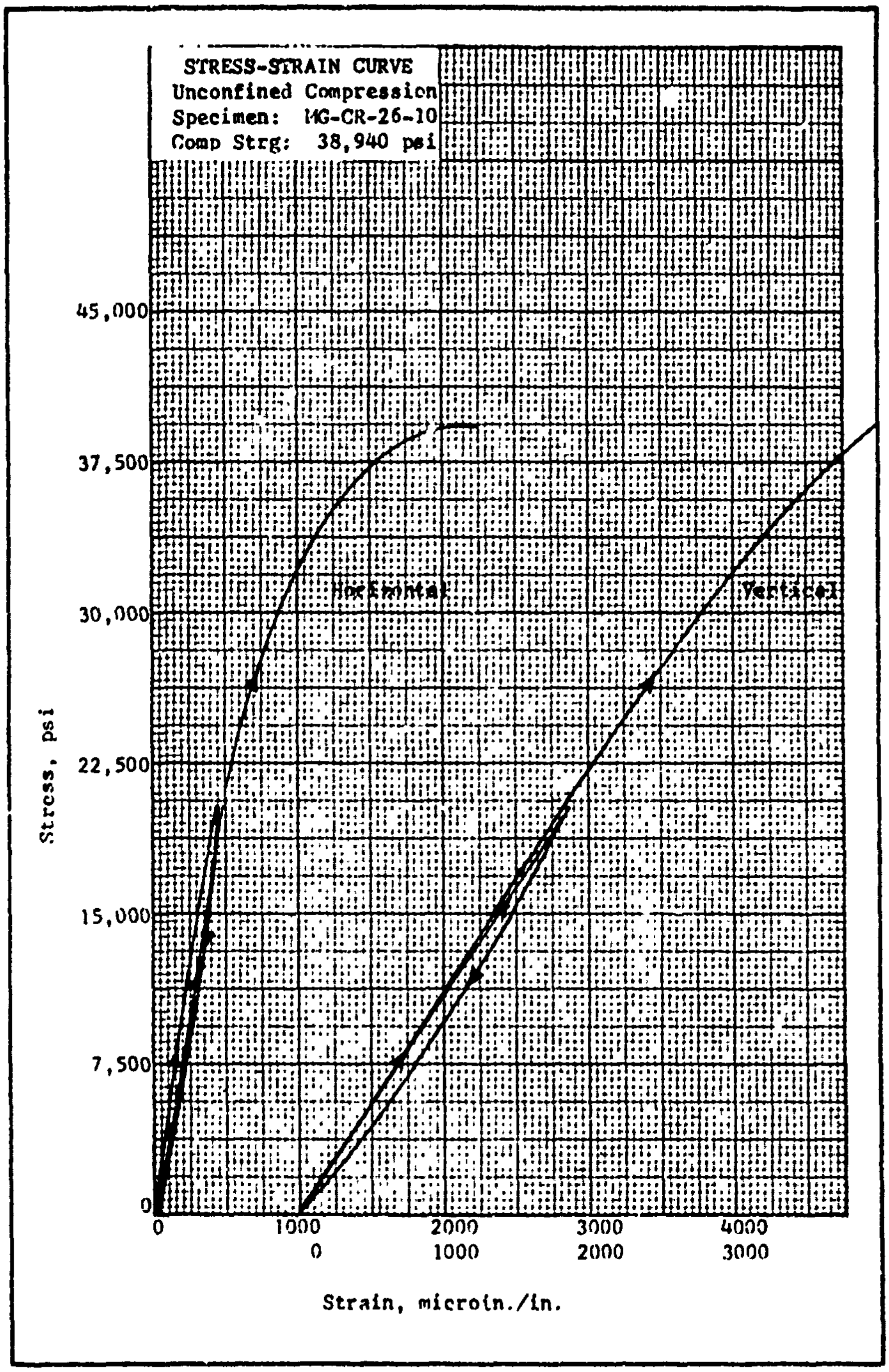

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: MG-CR-25-4
Comp Strg: 33,180 psi
Horizontal
Vertical
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
Stress, psi
0
1000
2000
3000
4000
0
1000
2000
3500
Strain, microin./in.

PLATE D2



STRESS-STRAIN CURVE
Unconfined Compression
Specimen: MG-CR-26-10
Comp Strg: 38,940 psi
Stress, psi
45,000
37,500
30,000
22,500
15,000
7,500
0
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE D3

APPENDIX E

DATA REPORT

Hole MG-CR-28

4 September 1969

Hole Location: Baraga County, Michigan

Longitude: 88° 17'15" West

Latitude: 46° 39'31" North

Township 49N, Range 32W, Section 10-SW 1/4, NE 1/4

Core

1. The following core was received on 1 July 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	7
2	18
3	28
4	38
5	47
6	57
7	68
8	77
9	87
10	88
11	96
12	104
13	114
14	126
15	134
16	145
17	154
18	165
19	174
20	183
21	192
22	200

Description

2. The samples received were light to dark gray-colored rock identified as quartz mica gneiss by the field log received with the core. Numerous pegmatite dikes and intrusions were noted. Piece Nos. 15, 18, and 21 contained tightly closed fractures.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below:

Sample No.	Description	Core Depth	Sp Gr	Schmidt No.*	Comp Strg, psi	Comp Wave Vel, fps
1	Fine Grained Tonalite	7	2.790	63.8	35,750	18,715
2	Vertical Fractured Tonalite	18	2.988	61.8	18,480	20,655
5	Fine Grained Tonalite	47	2.705	63.8	29,820	18,985
6	Vertical Fractured Tonalite	57	2.797	63.2	22,910	19,760
8	Pegmatite	77	2.658	65.2	30,610	19,445
10	Pegmatite	87	2.677	--	35,000	19,010
18	Pegmatite	165	2.671	63.8	41,200	19,375
[illegible]	Dark Tonalite High Angle Fracture	192	3.037	63.7	26,580	21,950
22	Medium Grained Tonalite	200	2.898	56.7	32,730	20,600
Average of Pegmatite Specimens (3)			2.669	64.0	35,605	19,275
Average of Fine Grained Specimens (2)			2.748	63.8	32,785	18,850
Average of Medium Grained Specimens (4)			2.930	61.4	25,175	20,740

* Schmidt hammer test not conducted on several specimens due to possibility of breakage.

Moduli of deformation

4. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 1, 8, and 22. Stress-strain curves are given in plates 1, 2, and 3. Specimens 1 and 22 were cycled at 20,000 psi. Specimen 8 was cycled at 25,000 psi. Results are given below.

Specimen	Modulus, psi x 10^6			Shear	Poisson's
No.	Young's	Bulk	Shear	Velocity, fps	Ratio
			Dynamic Tests		
1	10.0	8.0	3.9	10,160	0.29
8	10.6	8.0	4.2	10,805	0.28
22	11.9	10.4	5.6	10,815	0.31
			Static Tests		
1	11.6	5.0	4.8	--	0.22
8	11.6	5.9	5.0	--	0.17
22	12.5	8.5	5.0	--	0.25

All of the rock tested herein is apparently rather rigid material exhibiting little hysteresis.

Conclusions

5. The core received from hole MG-CR-28 was identified as light to dark gray quartz mica gneiss by the field log received with the core. Numerous pegmatite dikes and intrusions were noted. Specimens 15, 18, and 21 contained tightly closed fractures. Unconfined compressive tests indicated that the pegmatite and fine grained materials were appreciably stronger than the medium grained materials, strength of the medium grained specimens generally being approximately 75 percent of the strength exhibited by the other two groups. Banding and high angle fracuring seemed to have no significant effect on unconfined compressive strength of this material.

Property	Pegmatite Specimens	Fine Grained Specimens	Medium Grained Specimens
Specific gravity	2.669	2.748	2.930
Schmidt number	64.0	63.8	61.4
Compressive strength, psi	35,605	32,785	25,175
Compressional wave velocity, fps	19,275	18,850	20,740
Static Young's modulus, psi x 10^{-6}	11.6	11.6	12.5

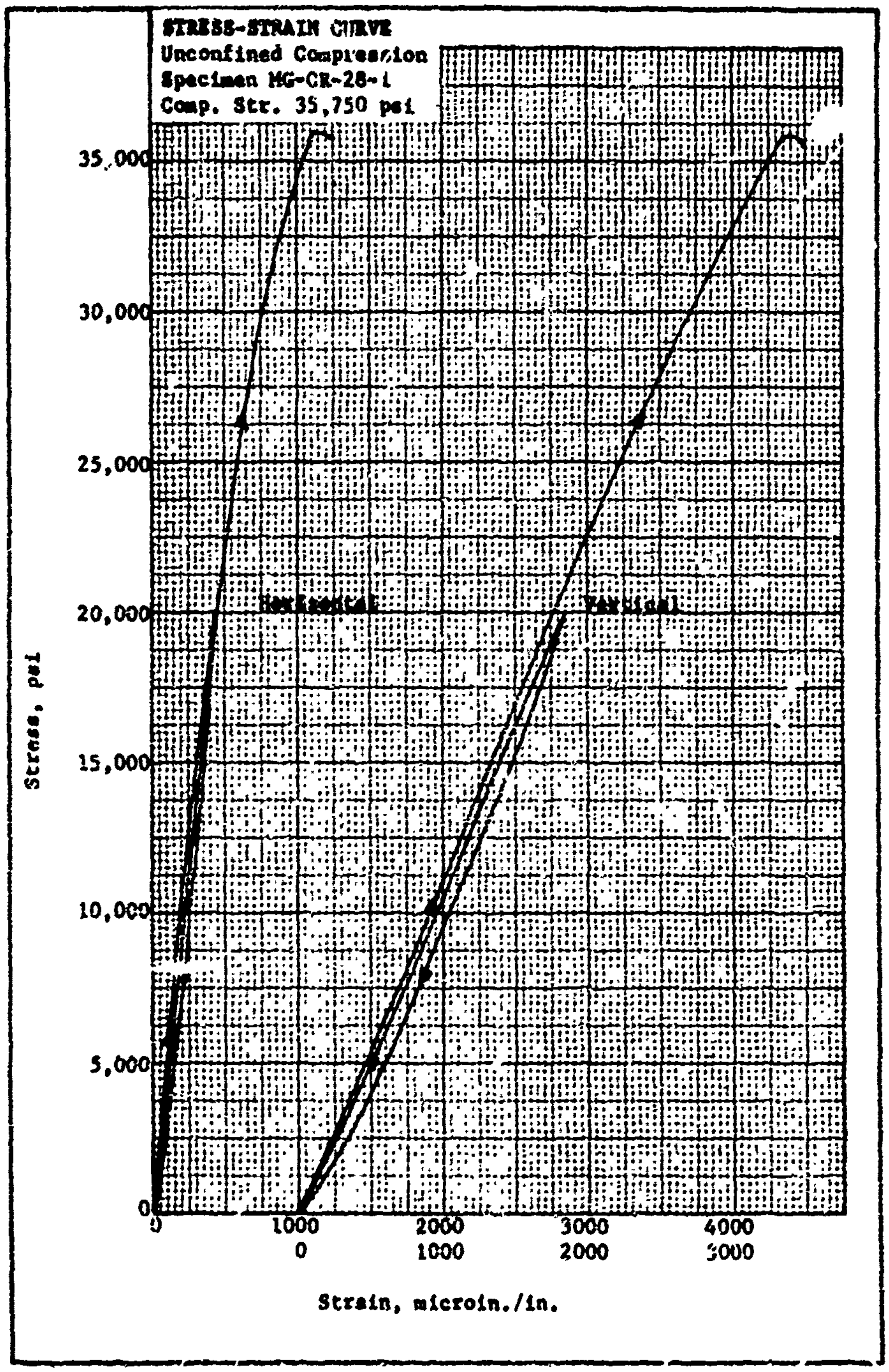

STRESS-STRAIN CURVE
Unconfined Compression
Specimen MG-CR-28-1
Comp. Str. 35,750 psi
Horizontal
Vertical
Stress, psi
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE E1

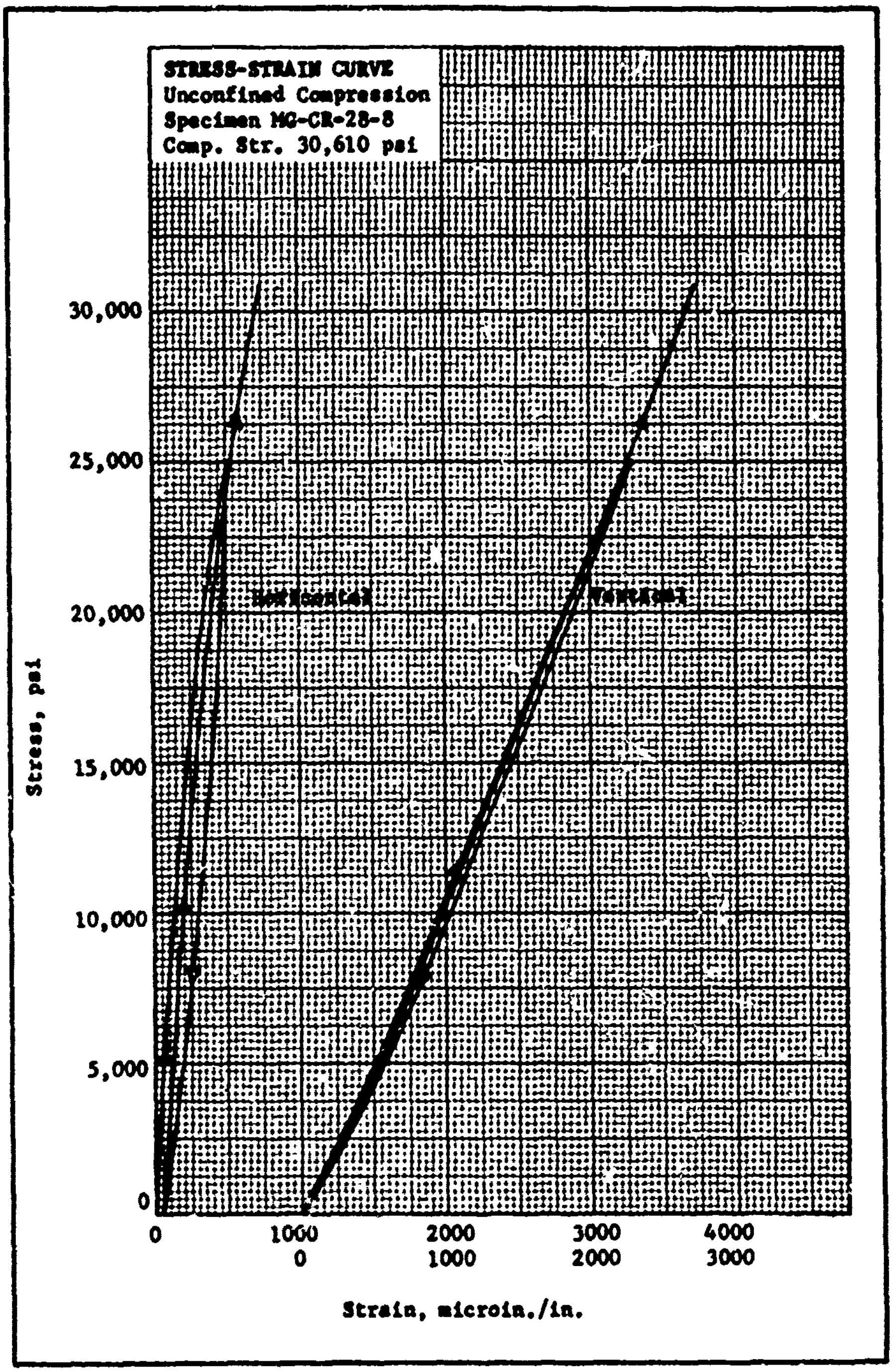

STRESS-STRAIN CURVE
Unconfined Compression
Specimen MG-CR-28-8
Comp. Str. 30,610 psi
30,000
25,000
20,000
15,000
10,000
5,000
0
Stress, psi
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE E2

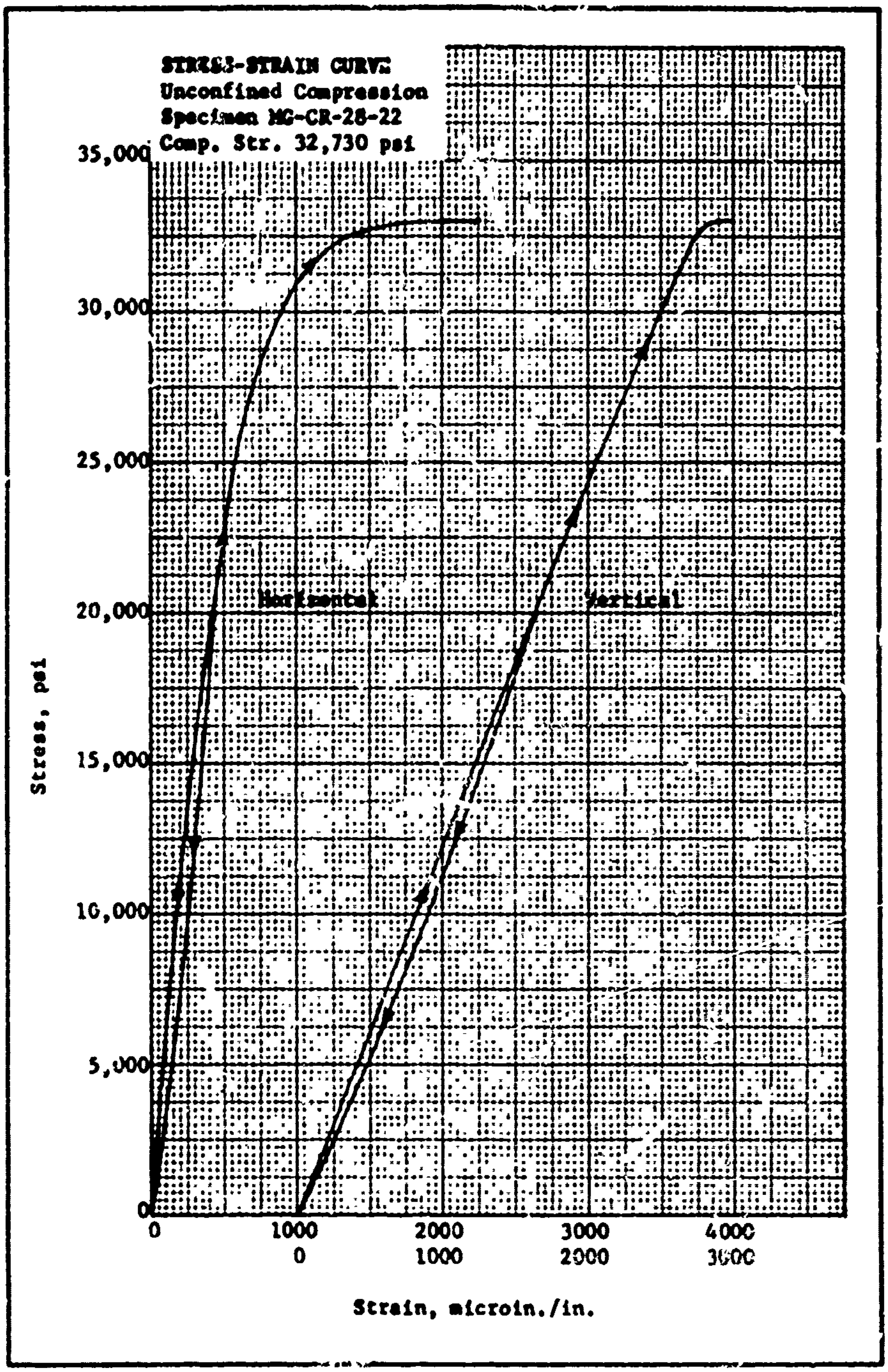

STRESS-STRAIN CURVE
Unconfined Compression
Specimen MG-CR-28-22
Comp. Str. 32,730 psi
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
Stress, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE E3

APPENDIX F

DATA REPORT

Hole MG-CR-54

11 September 1969

Hole Location: Marquette County, Michigan

Longitude: 87° 53' 45" West

Latitude: 46°.40' 38" North

Township 30N, Range 29W, Section 35, S 1/2 SE 1/4

Core

1. The following core was received on 5 September 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	7
2	15
3	28
4	35
5	47
6	55
7	68
8	79
9	85
10	95
11	105
12	117
13	125
14	140
15	147
16	157
17	167
18	177
19	187
20	195

Description

2. The samples received were gray- to green-gray-colored rock identified generally as a migmatite complex by the field log received with the core. All samples appeared to be metamorphosed igneous rock except Nos. 1, 9, and 11 which consisted predominantly of dark green amphibolite. All samples contained healed, randomly oriented, fractures or joints.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below:

Sample No.	Description	Core Depth	Sp Gr	Schmidt No.	Comp Strg, psi	Comp Wave Vel, fps
1	Highly Fractured Amphibolite	7	2.714	37.3	8,790	18,940
2	Highly Fractured Tonalite	15	2.667	--	16,360	19,470
6	Highly Fractured Tonalite	55	2.644	--	3,080	19,540
7	Highly Fractured Tonalite	68	2.653	41.8	16,480	19,410
8	Highly Fractured Tonalite	79	2.653	--	2,910	19,360
9	Highly Fractured Amphibolite	85	2.866	--	4,950	21,620
11	Highly Fractured Amphibolite	105	2.745	--	3,580	20,680
14	Moderately Fractured Tonalite	140	2.704	49.7	17,000	19,670
18	Moderately Fractured Tonalite	172	2.658	--	5,940	19,880
20	Moderately Fractured Tonalite	195	2.668	--	5,880	19,550
Average of Specimens Which Failed on Fractures (7)			2.707	37.3	5,020	19,940
Average of Specimens Not Influenced by Fractures (3)			2.675	45.8	16,610	19,520

The Schmidt hammer test was not conducted on many of the specimens due to the possibility of breakage. Visually, the rock appeared to be a rather competent material. Specific gravity and wave velocity measurements did not detect the detrimental effect of the fracturing. Although tightly closed, the fractures and joints significantly reduced the compressive

strength. These results represent the first indication of incompetent material in the Michigamme Area.

Moduli of deformation

4. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 1, 8, and 18. Stress-strain curves are given in plates 1, 2, and 3. Specimens 1 and 18 were cycled at 5000 psi. Results are given below.

Specimen No.	Modulus, psi x 10^6 Young's	Modulus, psi x 10^6 Bulk	Modulus, psi x 10^6 Shear	Shear Velocity, fps	Poisson's Ratio
			Dynamic Tests		
1	8.9	8.7	3.4	9,570	0.33
8	9.5	8.6	3.6	10,050	0.32
18	9.8	9.2	3.7	10,160	0.32
			Static Tests		
1	9.9	4.7	4.3	--	0.15
8	9.3	6.2	3.7	--	0.25
18	9.7	6.5	3.9	--	0.25

5. The moduli indicate that the rock, although fractured, is a relatively rigid material. Apparently the fractures are well healed or closed. The stress-strain curve for specimen No. 1 indicates some crack closure at the lower stress levels; however, no closure is indicated on specimen Nos. 8 and 18. Some hysteresis is also evident in the curve obtained on specimen No. 1.

Conclusions

6. The core received from hole MG-GR-54 was green- to gray-colored rock identified as being a migmatite complex by the field log received with the core. The samples received were predominantly metamorphosed igneous rock. All specimens contained tightly closed fractures. Unconfined compressive tests indicated that fractures oriented at critical angles appreciably reduced the compressive strength compared to specimens in which fracturing apparently did not affect the strength results. The stress-strain curves indicated little crack closure and little hysteresis.

Property	Specimens Which Failed on Fractures	Failure Not Influenced by Fractures
Specific Gravity	2.707	2.675
Schmidt Number	37.3	45.8
Compressive Strength, psi	5,020	16,610
Compressional Wave Velocity, fps	19,940	19,520
Static Young's Modulus, psi x 10^{-6}	9.6	--

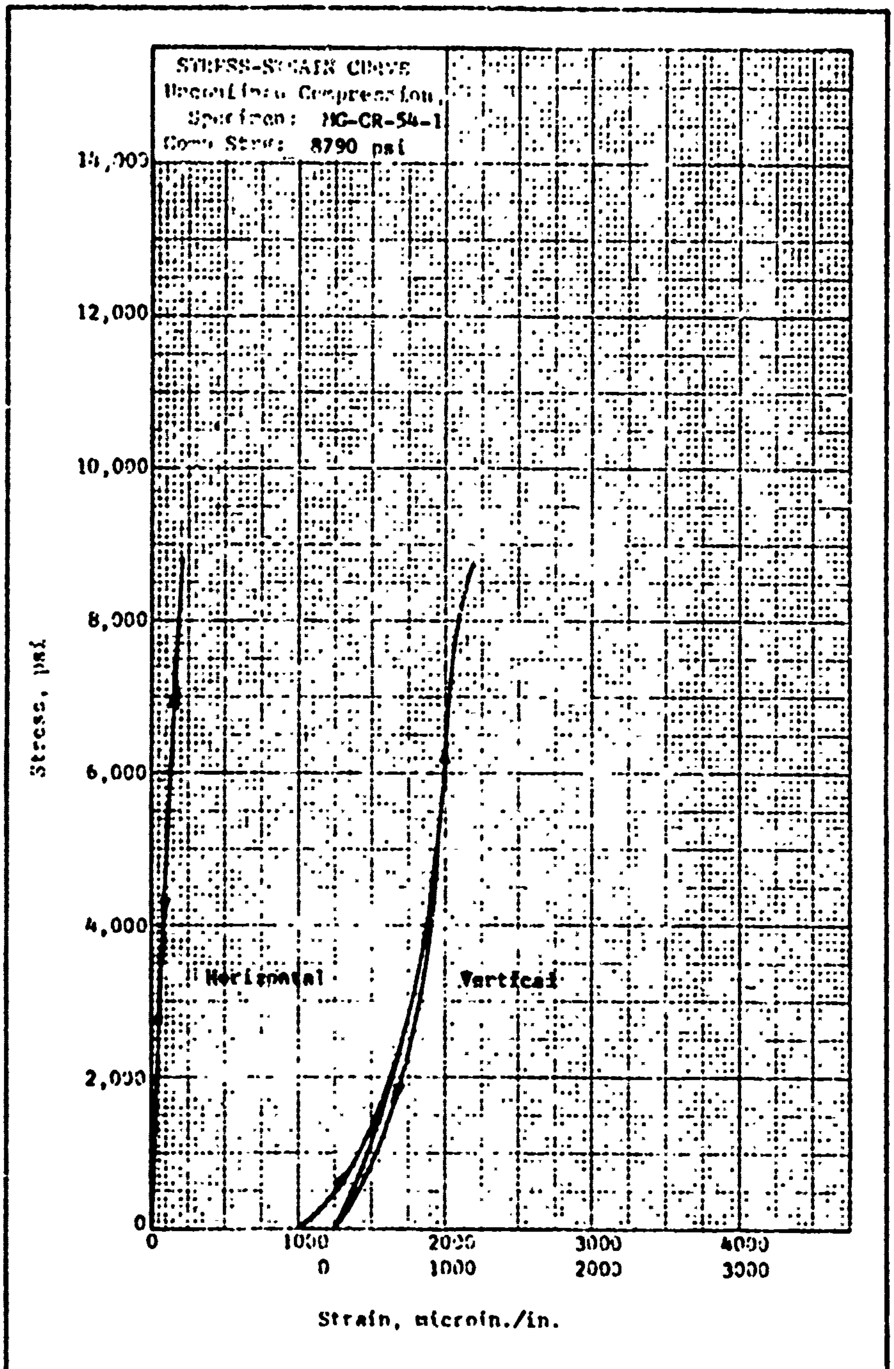

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: MG-CR-54-1
Comp Str: 8790 psi
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Stress, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE F1

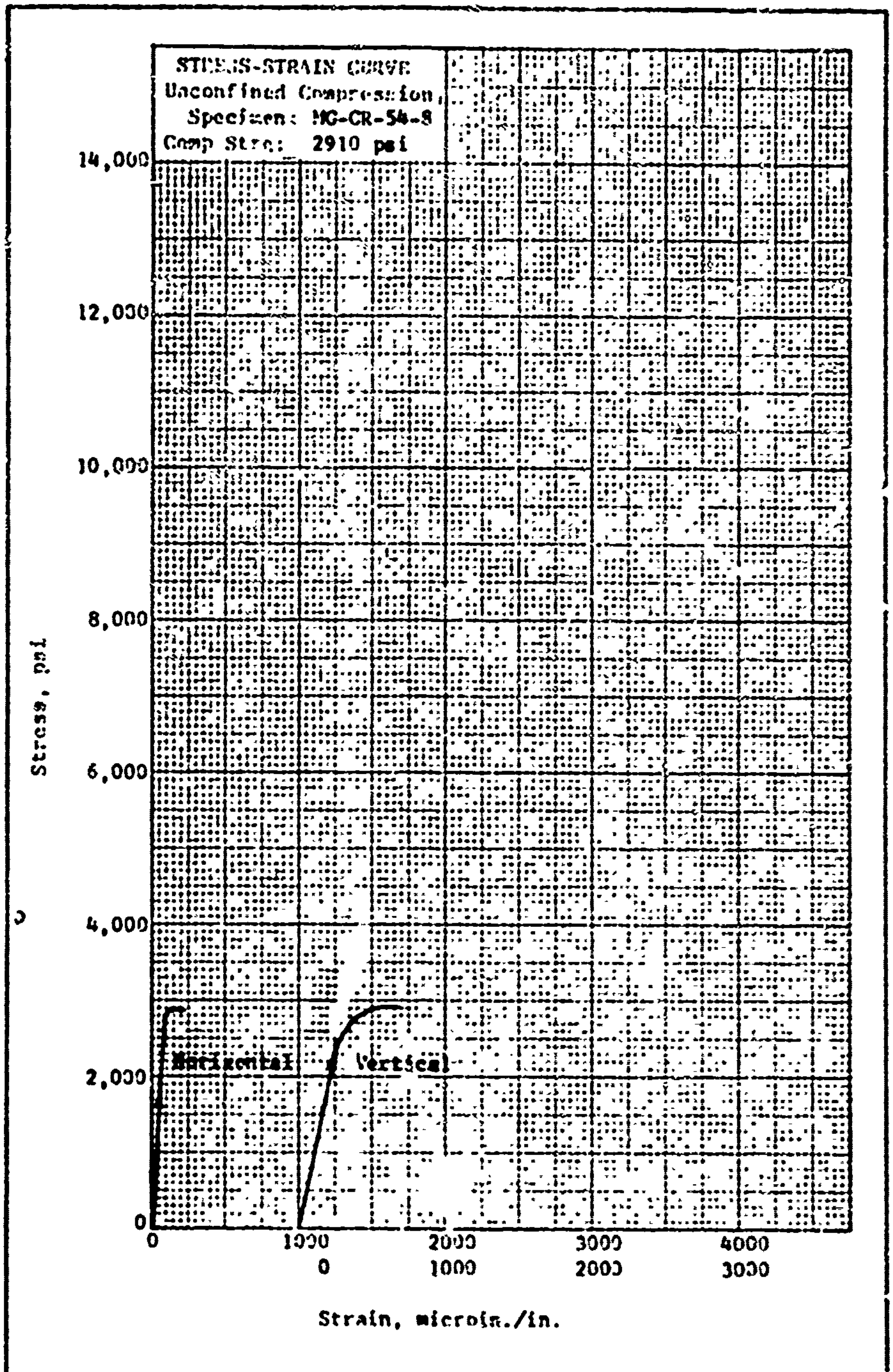

STRESS-STRAIN CURVE
Unconfined Compression,
Specimen: MC-CR-54-8
Comp Str: 2910 psi
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Stress, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE F2

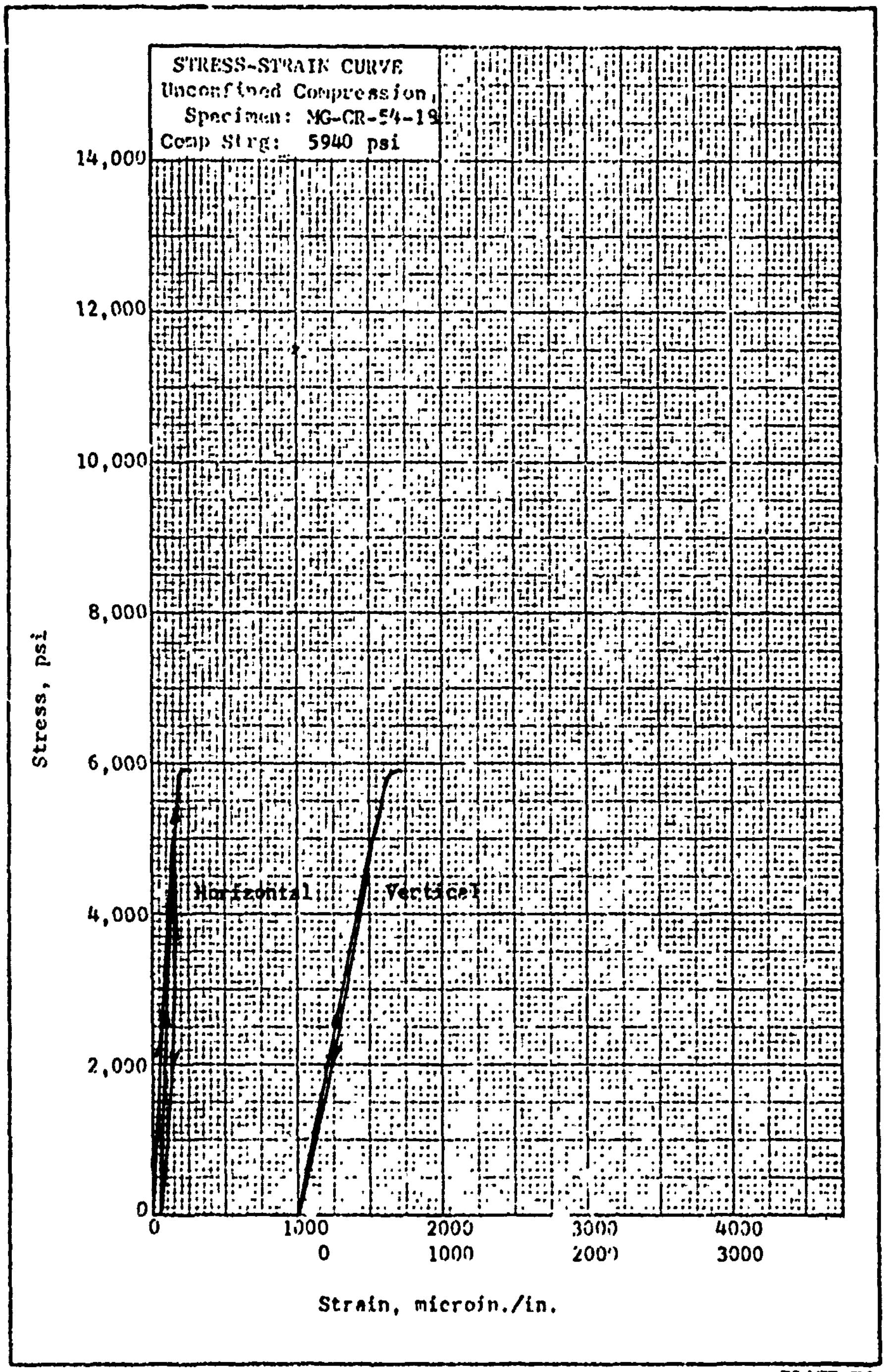

STRESS-STRAIN CURVE
Unconfined Compression,
Specimen: MG-CR-54-19
Comp Strg: 5940 psi
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Stress, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE F3

REFERENCES

1. D. U. Deere and R. P. Miller; "Engineering Classification and Index Properties for Intact Rock"; Technical Report No. AFWL-TR-65-116, December 1966; Air Force Weapons Laboratory, Kirtland Air Force Base, N. Mex.; Unclassified.

2. U. S. Army Engineer Waterways Experiment Station, CE; "Handbook for Concrete and Cement"; August 1949 (with quarterly supplements); Vicksburg, Miss.; Unclassified.

3. S. J. Shand; "Eruptive Rocks"; Third Edition, 1947; John Wiley and Sons, New York, N. Y.; Unclassified.

4. C. A. Lamey; "Republic Granite or Basement Complex?"; Journal of Geology, 1937, Vol. 45, Pages 487-510; University of Chicago Press, Chicago, Ill.; Unclassified.

5. R. M. Dickey; "The Granitic Sequence in the Southern Complex of Upper Michigan"; Journal of Geology, 1936, Vol. 44, Pages 317-340; University of Chicago Press, Chicago, Ill.; Unclassified.

6. H. L. James; "Zones of Regional Metamorphism in the Precambrian of Northern Michigan"; Bulletin of the Geological Society of America, December 1955, Vol. 66, Pages 1455-1488; Baltimore, Md.; Unclassified.

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13. ABSTRACT

Laboratory tests were conducted on rock core samples received from six core holes in the Michigamme study area of Marquette and Baraga Counties near Sawyer Air Force Base, Michigan. Results were used to determine the quality and uniformity of the rock to depths of 200 feet below ground surface. The rock core was petrographically identified as predominately tonalite, potash granite, and amphibolite, with relatively minor amounts of biotite schist and pegmatite. Most specimens contained fractures which ranged in orientation from horizontal to vertical. Several specimens contained well-developed systems of fracture. Evaluation on a hole-to-hole basis indicates the potash granite removed from Hole MG-CR-2A and the gneissic tonalite and amphibolite removed from Holes MG-CR-26 and -28 to be relatively competent to very competent rock. These holes represent materials which should offer good possibilities as a competent, hard rock medium. Hole MG-CR-18 yielded specimens of potash granite, tonalite, and amphibolite. This variety of materials exhibited physical characteristics generally representative of marginal to good quality rock, and should offer some possibility as a competent hard rock medium, provided the single zone of incompetent rock is not a disqualifying factor. The tonalites, amphibolites, and potash granites representative of Holes MG-CR-10 and -54 were generally fractured and exhibited physical characteristics typical of incompetent rock and of lower quality than that required of competent media. The above evaluations have been based on somewhat limited data, and, therefore, more extensive investigation will be required in order to fully define the individual areas under consideration.

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Rock cores						
Rock properties						
Rock tests						

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